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DEALING WITH DECOUPLED NUCLEAR EXPLOSIONS UNDER A COMPREHENSIVE TEST BAN TREATY

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The detonation of nuclear explosions in large underground cavities so as to muffle or decouple the seismic waves they generated has been debated for more than 35 years. This report reviews the history of the decoupling concept, assesses what countries have the technological capabilities to carry out such a test of a given yield, and evaluates a number of decoupling scenarios. I conclude that testing with large decoupling factors, DF, is feasible for yields of a few kilotons (kt) or larger only in cavities in salt domes. Past nuclear explosions conducted in salt for which cavities may remain standing that are large enough for the full decoupling of explosions with yields ≥ 0.5 kt are concentrated in only a few areas of Kazakhstan and Russia. The existence of all cavities of that size that were created by past nuclear explosions is known since the explosions that created those cavities must be at least 20 times larger in yield than the size of a fully decoupled event that can be detonated in them. Hence, the monitoring of cavities created in that way that may remain standing should be relatively easy at the 1 kt level if appropriate verification measures are put in place. While large cavities can be created in salt by solution mining, no country is known to have evacuated such a cavity of brine and then conducted a decoupled nuclear explosion in it. Air-filled

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cavities in salt suitable for significant decoupled testing are stable over only a very narrow range of depths from about 200 m to a maximum of 900 to 1300 m. Most areas of thick salt deposits in the Former Soviet Union and the U.S. are typified by efficient transmission for seismic waves and low natural seismic activity. The scaled cavity radius of 20 m cited in the literature for full decoupling in granite is poorly determined, probably is too small, and has resulted in overestimates of the potential to employ cavities in hard rock for decoupled nuclear testing. For cavities in hard rock, lack of any known experience in conducting decoupled nuclear testing in them, insuring containment in the presence of large differences in principal stresses and the presence of joints and other inhomogeneities on a scale of 1 to 100 m, and the excavation of such a large cavity without being detected are factors that make clandestine decoupled testing of a few kt or larger very unlikely for sites in hard rock, even for countries with considerable testing experience. Decoupled testing of large DF in any media at such yields by countries lacking containment experience would be very difficult to carry out so to have high assurance of maintaining secrecy.

CONTENTS

1. Introduction

The detonation of nuclear explosions in large underground cavities--so-called muffled or decoupled testing-- constitutes the greatest challenge to verification efforts under a Comprehensive Test Ban Treaty (CTBT). This evasion scenario along with assessments about what countries are capable of conducting nuclear tests with large decoupling factors, DF, sets a limit on how low a yield can be effectively verified. The United States working paper for the Committee of Disarmament of May 1994 [1] states that the international monitoring system for a CTBT should be capable of detection and identification of nuclear explosions down to a few kilotons (kt) yield or less, even when evasively conducted. The work on decoupled testing described here are mainly in the context of identification at the few kiloton level both for countries that have considerable underground testing and containment experience, like the former Soviet Union (FSU) and the U.S.A., and countries that might attempt to test nuclear devices clandestinely for the first time.

The work of my colleagues and me [2-6] of the past few years addresses a number of aspects of the problem of clandestine nuclear testing in large cavities in salt domes, bedded salt and hard rock. Dealing with decoupled testing involves information and expertise from the following wide variety of disciplines that often have not interacted much with one another and which usually publish separately--the physics of nuclear explosions, construction and stability of large underground cavities in salt and hard rock, the mineralogy and rheology of various evaporate minerals including halite (NaCl), the state of stress in the crust, the geology of various countries, containment of underground nuclear explosions, the conduct of chemical explosions for various industrial purposes, solution mining in salt, high-level radioactive waste disposal in salt and hard rock, seismic monitoring, and the use of complex computer codes to model a wide range of stresses and strains involved in tamped and decoupled nuclear explosions, the seismic waves they generate and other observable physical parameters of nuclear and chemical explosions.

In this report I attempt to assess and synthesize information from this extensive and widely-distributed literature as it bears upon what types of evasion scenarios are either probable or plausible for conducting clandestine nuclear tests under a CTBT. I emphasize geological and engineering constraints, information on decoupled nuclear and chemical explosions conducted by various countries, seismic identification levels, the requirement of insuring containment (i.e., to have high confidence that no bomb-produced fission products reach the surface and that no noticeable surface effects are produced), and on the need of a country attempting to test clandestinely to have a high level of confidence that it can do so without being caught cheating.

This report first reviews the monitoring requirements for verifying a CTBT using the Former Soviet Union as an example and applies it briefly to other countries including the other nuclear powers and countries judged to be potential nuclear proliferators during the next decade. Both non-evasive and evasive testing are examined including testing in a variety of rock types. I next discuss the development of the decoupling concept in the late 1950s in the United States [7], early estimates of decoupling factors, the sizes (i.e., yields, Y) of nuclear explosions that might be tested in that manner and the technology of creating huge underground cavities [7-8], and claims by Killian [9], Eisenhower's Science Advisor during that era, that the decoupling hypothesis was overwhelmingly a political concept used by proponents of nuclear testing and weapons development to argue that great scientific and technical impediments stood in the way of effectively monitoring a treaty to ban underground nuclear testing.

In 1959, the U.S. conducted a series of chemical explosions in salt called the Cowboy experiments to test the decoupling concept and in 1966 fired the Sterling nuclear explosion in the cavity created in a salt dome by the 5.3 kt Salmon explosion. In the subsequent 25 years, it was common in the United States for several of the few individuals who continued working on decoupling to extrapolate the results of the 1959 and 1966 experiments from the very small yields of Cowboy (up to 2000 lb. or 0.9 meter tons) and Sterling, 0.38 kt, to yields as large as 10 and even 100 kt. Most work in the U.S. on nuclear verification from 1974 until 1991 was focused on accurate determination of yields of Soviet underground nuclear explosions in conjunction with the 150-kt yield limitation of the Threshold Test Ban Treaty (TTBT). Relative little attention was paid to either identification of seismic events of small magnitude or decoupled testing. That situation

changed in the last 5 years with the renegotiation and ratification of the TTBT, the breakup of the Soviet Union, and the change in U.S. policy in favor of negotiating a CTBT, greater emphasis on limiting the proliferation of nuclear weapons, and concern about extending the Non-Proliferation Treaty, which ends in 1995 unless its term is extended.

Since the Soviet Union was known to have tested a number of peaceful nuclear explosions (PNEs) in thick deposits of salt, several workers and policy makers in the United States concluded that the Russians must know much more about decoupling than was known in the U.S. In fact, before 1992 very little information had been released on Soviet explosions in salt. Since then several papers and reports have been published about Soviet nuclear explosions in salt [10-12]. Perhaps the most important set of data pertains to an 8 to 10 kt partially decoupled nuclear explosion that was detonated in March 1976 in the cavity in a salt dome formed by an explosion of 64 kt in 1971 near the small town of Azgir in western Kazakhstan. The 1976 event was recorded at local (up to 113 km), regional and teleseismic (greater than 20^{o}) distances. Its yield was more than 20 times larger than Sterling, making it a much better experiment for ascertaining seismic magnitudes, decoupling factors, identification capabilities and evasion possibilities for decoupled events in the range 1 to 10 kt. In addition, information provided by Russian scientists indicates that 6 very small nuclear explosion with yields between 0.01 and 0.5 kt (1 to 500 tons) were detonated between 1975 and 1979 in the water-filled cavity created by the 25-kt Azgir explosion of 1968 [3, 11-13]. Hence, those 6 shots were not *decoupled* nuclear explosions but, in fact, exhibited *enhanced* seismic coupling at frequencies near that of the fundamental resonance frequency of the water-filled cavity [3, 13].

Now that a CTBT is under negotiation, many issues involving verification that have largely been dormant for many years are surfacing. Several aspects of decoupled nuclear testing are among the prime issues. A strenuous debate has been going in the U.S. about clandestine testing in large cavities in salt and hard rock, the stability of such cavities for nuclear testing and whether they could be reused, the maximum yields of decoupled explosions that could be tested, the DF of explosions that are either overdriven (and hence partially decoupled) or set off in cavities that depart significantly from a spherical geometry, whether the seismic signals of decoupled events could be masked by setting them off at the time of a nearby large chemical explosion, and whether countries that lack experience with underground testing and confinement would attempt to or could conduct a decoupled nuclear test of significant yield. Some of the conclusions about these issues that were reached in the 1988 study by the Office of Technology Assessment [14] have recently been challenged by Stevens et al. [15-16], Murphy et al. [17], Leith and Glover [18] and the 1994 issue paper on decoupling opportunities by Knowles et al. [19] of the U.S. Defense Nuclear Agency. Most of the issues they raise are re-examined in this report and a variety of decoupling scenarios is evaluated.

In the last 25 years a great deal of experience has been obtained by the U.S. and several European countries on the rheological properties of salt in conjunction with research on radioactive waste disposal in salt deposits and by industry on the construction and stability of large cavities in salt for petroleum storage and waste disposal. Experience with very large cavities in salt domes is now available from the U.S. Strategic Petroleum Reserve as well as from Europe, the FSU and other parts of the U.S. on cavities created in salt for gas storage and on their stability (or lack thereof).

The following conclusions are reached in this report. Decoupled testing in large underground cavities created by solution mining by those countries that already possess considerable underground testing experience--Russia, the U.S. and perhaps China--constitutes the greatest challenge to the monitoring of a CTBT at the few to 10 kt level. No country, however, is known to have conducted a nuclear explosion of significant decoupling factor and yield in a cavity created by either solution mining in salt or in hard rock. Hence, any country wanting to conduct such a decoupled test under those conditions would have to contend with considerable scientific and technical uncertainty. This lack of experimentation has led to different assessments about the feasibility or possibility of conducting clandestine nuclear tests of those types for 35 years.

Throughout the history of the debate about the feasibility of decoupled testing, the scientific and policy communities have not agreed who must bear the burden of proof for untested hypotheses.

From known U.S. and Russian experience in conducting and detecting decoupled explosions and in constructing large cavities, I conclude that nuclear testing with large decoupling factors, DF, is feasible in the yield range from a few to 10 kt only in cavities in salt domes. Only Russia and Kazakhstan possess cavities created by past nuclear explosions in salt of sufficient size to fully decouple explosions of 0.5 to several kilotons. Those sites are few, are located in regions of low natural earthquake activity and could be relatively easily monitored under a CTBT. Sites suitable for the construction of large cavities in salt domes by solution mining exist in several places in Russia, China and the U.S.

The cavity radius of 20 m times $Y^{1/3}$ cited in the literature for full decoupling of explosions in granite of significant yield is an early estimate that is poorly determined and probably is too small. It recent use has resulted in overestimates by Leith and Glover [18], Knowles et al. [19] and others of the potential to employ cavities in hard rock for significant decoupled nuclear testing. For cavities in hard rock, lack of known experience by any country in conducting decoupled nuclear testing of those yields, insuring containment in the presence of large differences in principal stresses and the presence of joints and other inhomogeneities on a scale of a few meters to hundreds of meters, and the excavation of such a large cavity without detection are factors that make clandestine decoupled testing of a few kilotons or larger very unlikely for sites in hard rock even for countries with considerable testing experience. Nevertheless, resolving the question of the feasibility of decoupled testing at the few kiloton level for hard rock is critical since hard rock is present in many more areas than salt domes. Large chemical explosions are rare in salt deposits but more common in hard rock. Thus, resolution of this issue will determine whether the number of large chemical explosions that need to be discriminated from possible decoupled nuclear explosions is very small in the former or larger in the latter case.

Nuclear testing at large decoupling factors in any media at yields of a few kilotons or larger by countries lacking containment experience would be very difficult to carry out so to have high assurance of maintaining secrecy. For any country to believe that it can cheat on a CTBT with high confidence by testing in a decoupled mode at the few kiloton level or larger, it must be prepared to pass a series of verification challenges: construction and evacuation of a large cavity at depth without detection, have confidence in cavity stability, insure containment of bomb-produced isotopes such as those of Xenon, use enough equipment and cables to monitor the explosions but yet not have their presence identified by satellite imagery or their recent use detected by an on-site inspection, and have high assurance that the explosions will not be identified by seismic or other means. Thus, much more than being able to construct a large underground cavity is required for a country to have high confidence that a decoupled nuclear test of significant yield will not be identified by other countries.

2. Capabilities of Seismic Networks for Identifying Decoupled Explosions

Figure 1 indicates the expected seismic bodywave magnitudes, m_b, of contained underground nuclear explosions of various yields in the Former Soviet Union (FSU), most of which now consists of the Commonwealth of Independent States (C.I.S). The range of m_b's for tamped (fully coupled) events in hard rocks and water-saturated rocks covers reports in the literature for differences in coupling near shot points in the geological media indicated as well as differences in the attenuation of seismic P waves transmitted to teleseismic distances (here taken to be greater than 20^o or 2200 km). The upper limits of possible underground testing in Figure 1 are taken to be the present 150-kt limit of the TTBT for hard rocks and water saturated rocks; the upper limit of 10 kt for conducting clandestine testing in large cavities in salt domes is described in the 1988 OTA Report [14]. Note that the line labeled SW Shagan River on Figure 1, which pertains to the former main test site of the Soviet Union in eastern Kazakhstan, a hard rock site with low attenuation (efficient transmission) for P waves, falls near the top of that regime as do the data points for the

three explosions in salt at Azgir. Salt is a good coupling geological medium as discussed in section 7.4.

The 1988 OTA Report [14] described the identification threshold as of 1988 for the C.I.S. as m_b 4.0. Identification thresholds for seismic events, of course, are higher than detection thresholds, typically by about 0.5 m_b units. The 1988 assessment did not included data from seismic stations within the FSU, such as that from the newer IRIS digitally-recording stations, standard stations of the U.S.S.R. or those of the Russian Ministry of Defense. At a capability of m_b 4.0, tamped explosions at Shagan River and those at Azgir would be identified down to several tenths of a kiloton; some events in hard rock and water saturated rock in areas of low P-wave attenuation of the C.I.S. might go unidentified for yields as large as nearly 3 kt.

For an identification threshold of m_b 4.0 the OTA Report concluded that fully decoupled explosions in salt domes of the U.S.S.R. might go unidentified for yields as large as 10 kt, a level largely set by the size of cavities that could be constructed and used clandestinely, the low levels of natural seismic activity and good transmission of seismic waves for most salt domes areas of the Former Soviet Union, and the fact that seismic signals from decoupled events larger than 10 kt would stand a good chance of being detected and possibly identified. Members of the panel that advised OTA on their 1988 study, of which I was a part, did not reach a consensus on what the identification threshold for the C.I.S. would be if data from a good internal seismic network were available in addition to data from external stations. There was agreement (p. 92) that "identification can be accomplished in the U.S.S.R. down to at least as low as m_b 3.5." The Report then states "Many experts claim that this identification threshold is too cautious and that with an internal network, identification could be done with high confidence down to m_b 3.0." The OTA Report went on to conclude (p. 109) that "Most experts agree that a high-quality network of internal stations combined with stringent treaty constraints, could monitor a threshold of around 5 kt."

The 1994 report by the U.S. Department of Defense on its plans to monitor a CTBT [20] states that capability estimates for the Primary (Alpha) network proposed for monitoring a CTBT indicate "that the three-station (including at least one array) detection threshold" will be "m_b 3.0 or less for most of North America and the Former Soviet Union." While that estimate is a detection and not an identification threshold, it neither includes data from the so-called Beta seismic network nor any classified capabilities of various nations.

In the following and subsequent usage in this paper the term full decoupling is taken to be a reduction in the amplitude of long-period (low-frequency) seismic waves by a factor of 70 (i.e. DF = 70) as explained in Section 3.3 Figure 1 indicates that an identification capability of m_b 3.5 would include many events in the FSU down to about 0.07 kt, and events in all hard rocks and those below the water table down to 0.75 kt but might not identify fully decoupled events as large as 10 kt. A capability to discriminate at m_b 3.0 would lead to the identification of fully decoupled events in salt domes down to yields of 2 to 4 kt. I take this to be equivalent to the objective [1] of obtaining an identification capability at the few kiloton level for fully decoupled nuclear explosions the Former Soviet Union.

The regime labeled "salt, fully decoupled" in Figure 1 pertains to areas of efficient transmission of seismic waves in the C.I.S, which includes most but not all salt domes. Most regions of the FSU consist of old rock units that transmit seismic waves efficiently. Salt domes in more seismically attenuating areas of the FSU are concentrated in the Republic of Tadzhikistan, which is now a separate country from the Russian Republic. A better identification capability for possible decoupled explosions in that area, if deemed necessary, could be furnished by a local seismic network or array. The major civil war that has been in progress in Tadjikistan for the last few years, however, would undoubtedly make the conduct of clandestine nuclear tests of any kind in that area very difficult, if not impossible, as long as the war continues. Also, it would likely limit or prohibit the operation of seismic stations in Tadjikistan until warfare is reduced. Likewise, conducting nuclear explosions in secrecy would be difficult for Iraq since its main regions of salt domes are located in areas dominated by Kurdish and Sunni populations, who have long been fighting with forces of the central government. A CTBT verification regime that would be in effect for decades would need to be flexible in terms of obtaining additional monitoring capabilities in

regions like Tadjikistan if political conditions there and in the rest of the C.I.S. change. Likewise, the operation of stations in Afghanistan, a critical area for monitoring surrounding nations, may become feasible once civil war ends in that country.

Dry porous media do not appear to be present in sufficient thicknesses anywhere in the C.I.S. such that explosions could be detonated in them clandestinely with yields larger than 1 to 2 kt (SIPRI Seismic Study Group [21]; Office of Technology Assessment [14]). In contrast, the great thicknesses of dry alluvium at the Nevada Test Site are extremely rare. Dry alluvium is essentially a mixture of dry sand and gravel. The low cohesive strength of dry alluvium , the fact that it undergoes significant compaction when nuclear explosions are fired in it, and the collapse of nearly all cavities in that material makes clandestine testing in dry alluvium a risky proposition. Thus, it is difficult to either guarantee or predict with high certainty that a surface depression will not develop above even a overburied explosion, as is the case for most past nuclear tests in that medium in Nevada [22]. Significant surface disturbances could readily be detected by satellite photography or air surveillance. Thus, these factors as well as the upper limit of 1 to 2 kt rules out clandestine testing in the FSU in dry alluvium for yields of concern here, a few kilotons or larger. More attention needs to be paid to ascertaining if dry alluvium exists in other countries of concern to monitoring a CTBT. If so, that testing option, although it risks creating a surface depression, would be much less expensive and time consuming for a potential proliferator than conducting a decoupled nuclear test in a large underground cavity.

Stevens et al. [16] and others imply that the C.I.S. could conduct clandestine nuclear explosions in dry materials other than alluvium such as dry tuff, which also is present at the Nevada Test Site (NTS). Dry tuff of significant thicknesses for even small nuclear tests appears to be present in the C.I.S. only in the Caucasus, including areas of Armenia and Georgia that are now separate republics. Again, a monitoring network in the vicinity of those deposits could provide better identification for that region if it were deemed necessary under a CTBT.

The OTA Report [14] focused upon the Soviet Union and concluded that between 1 to 2 and 10 kt the only plausible method of evasion is that of nuclear testing in large cavities in salt domes. It also concluded that no method of evading a good monitoring network is credible above 10 kt but that several evasion scenarios, including testing in cavities in bedded salt and in hard rocks, are possible below 1 to 2 kt. Hence, the next several sections are devoted to nuclear explosions in salt and to decoupling in large cavities in salt domes.

3. Development, Testing and Criticism of Decoupling Concept: 1959-1989

3.1 CONFIRMATION OF GENERAL CONCEPT WITH CHEMICAL EXPLOSIVES

The idea that the seismic waves from underground nuclear explosions detonated in large underground cavities could be considerably reduced in size, i. e. muffled or decoupled, compared to the those from a tamped explosion was proposed in 1959, presented in Congressional testimony in 1960 and published the open scientific literature in 1961 by Latter et al. [7]. A tamped explosion is one where there are insignificant void spaces between the nuclear device and the surrounding rock medium, and a fully decoupled event is one where there is a large enough void space between the device and the surrounding material that no damage is done to the surrounding material [23].

The general concept of decoupling was confirmed in the Cowboy experiments of 1959 where small (less than one metric ton) chemical explosions were set off in cavities excavated in a salt dome in Louisiana [24]. British investigators reached a similar general conclusion in the Orpheus experiment where chemical explosions, but with charges limited to 4 to 29 Kg, were detonated in cavities in limestone and granite. It was only learned in the early 1990s that the Soviet Union also carried out a series of chemical explosions in limestone in Kirgizia in 1960 to test the decoupling concept [13]. The latter were performed about 9 months after the decoupling concept was presented in late 1959 to a Russian delegation in Geneva by scientists from the U.S. and the U.K. [8]. At that conference the Soviet delegation at first expressed skepticism about the decoupling concept and then accused the U.S. and U.K. of using that evasion scenario to sabotage attempts to

reach agreement about measures to verify a nuclear test ban in all environments (see verbatim transcript in same volume as ref. [8] and Killian's comments on page 173 of his book [9].

Estimates made of the decoupling factor, DF, based on the initial analysis of the Cowboy experiments and theoretical calculations performed between 1959 and 1965 were later found to be too large. Herbst et al. [24] reported a salt-to-salt decoupling factor (i.e. a tamped to decoupled DF for both types of explosions in salt) of 100 from the Cowboy experiments. They also found a DF of 10 and 30 for chemical explosions in overdriven cavities, i.e. cavities that were not large enough for full decoupling to occur for the yield of the explosive used. Murphey et al. [25], however, remarked in 1961 about the difficulty of extrapolating the results of chemical explosions in cavities to nuclear explosions since the size of the spike of pressure produced by the shock wave and the longer-time (step) pressure histories differ for the two types of explosions. Herbst et al. [24] also mention (p. 969) that the larger spike-pressures for the Cowboy chemical explosions may require much smaller ratios of the step pressure to overburden pressure to insure complete elastic behavior for those shots that were detonated in cavities.

A decoupling factor of about 300 figures prominently in early reports about the decoupling concept [7-8, 26-27]. That number was a composite of four components: 1) close-in measurements of seismic amplitudes from the first underground nuclear explosion, Rainier, a tamped event in 1957 of 1.7 kt in tuff at NTS, 2) a calculation of a DF of about 50 for a fully decoupled explosion in tuff of the same yield as Rainier, 3) a rough extrapolation of that number by to stronger rocks like salt, and 4) a correction for detonation depth from that of Rainier, 240 m, to 1000 m. Terms 3) and 4) were estimated to be about a factor of 6. Herbst et al. [24] reported a DF of 100 for the Cowboy experiments and stated that it was consistent with a salt-to-tuff ratio of 300. Latter had reported a DF of 120 for the Cowboy experiments a year earlier in Congressional testimony [27].

Two reasons account for using the odd decoupling ratio of 300 for salt to tuff at that time. The original Geneva system of seismic stations proposed in 1958 to monitor a test ban was tied to the single small, tamped Rainier explosion of 1957. Even by 1959 experimental data on underground nuclear explosions were limited to tamped events in tuff at NTS. The first Russian underground explosion did not occur until 1961. Around 1960 the solution to a pulse of pressure applied to the wall of a spherical cavity in an elastic medium had been known for several decades. That theory was used to calculate elastic wave generation for a fully decoupled explosion in a cavity, i.e. for a cavity large enough that all of the surrounding material behaved elastically. It was not possible at that time to calculate seismic amplitudes for the non-linear strains involved in either tamped or partially decoupled underground explosions. As discussed in Sections 3.3.3 and 11.6, there is still a question about the accuracy of calculations performed by complex computer codes for non-elastic situations that were developed subsequent to the early 1960s. Thus, decoupling factors during the era 1959 to about 1965 could not be estimated directly from theory but had to be tied to an observation, such as that from Rainier, for the tamped portion of the calculation.

3.2 POLITICS OF THE DECOUPLING CONCEPT IN THE 1960s

Another aspect of early claims about the decoupling hypothesis was the very strong influence of a few individuals, particularly the physicists Albert Latter and Edward Teller [7-8, 27]. Within only about a year of its development, Latter and a few others presented the decoupling concept as a well-developed and well-tested hypothesis at a joint U.S.-U.S.S.R.-U.K. conference in Geneva [8] and hearings by the Joint Committee on Atomic Energy of the U.S. Congress [27]. Publication of the decoupling theory and data from the Cowboy experiments did not occur for almost another year. There is little question that the large decoupling factors presented by proponents of the decoupling concept, statements to the effect that monitoring networks being considered in negotiations would not be able to identify decoupled nuclear explosions as large as 50 or 100 kt and that it was feasible to construct cavities for such large decoupled shots [8, 26-27] played a major role in underground testing being excluded from the Limited Test Ban Treaty of 1963, which forbid the testing of nuclear weapons in the atmosphere, space and underwater. For example, Harold Brown, the Deputy Director of the Lawrence Livermore Laboratory in 1960,

wrote [26] that rather detailed engineering feasibility studies indicated that a cavity of 400 foot (122 m) radius at a depth of about 1 km was feasible to construct in either hard rock or salt. Most other proponents of big-hole decoupling at that time argued that such large explosions were possible only in cavities in thick deposits of salt. As discussed in section 11 construction of huge cavities, especially in hard rock, still remains contentious today; no country is known to have conducted a decoupled nuclear test of large DF in a cavity in hard rock.

In Congressional testimony in 1960 the following conversation occurred [Ref. 27, p. 93]: "Representative Holifield. Let us understand what that means. Does that mean that a 300-kiloton shot could be reduced in seismic recordings to a 1 kiloton recording?
Dr. Latter. Yes, sir. ..
Senator Gore. "Do you agree with that?
Dr. Romney. Yes, indeed."

Many public officials in the early 1960s were left with the view that it was both possible to construct a cavity suitable to fully decouple 300 kt and that such a shot would not be detectable even with much improved seismic networks since its signal would be like that of a 1 kt explosion.

In 1960 Latter [8, 27] and Teller [27] each discussed methods, such as the introduction of heat-absorbing materials like carbon into a cavity, whereby the total amount of decoupling likely could be increased by another factor of about 10, i. e. to a DF of 2000 to 3000. In his Congressional testimony of 1960, Hans Bethe [Ref. 27, pp. 176-177], however, stated that some of the schemes for further decoupling were "in a completely different category from the primary scheme of decoupling by a big hole." In his testimony he went on to describe the difficulties with these exotic schemes.

Bethe concluded "It is my opinion that the next round [of technical advance] ought to go to the detection rather than to the concealment." Teller, however, stated earlier in the hearing [Ref. 27, p. 160] "My hunch is that further developments may continue to go in the direction that we shall learn more about concealment and that it will be quite difficult for methods of detection to catch up with methods of concealment." Subsequent small nuclear tests in Nevada showed that obtaining further decoupling by using carbon particles in cavities was not feasible [28]. The history of research and development in nuclear detection of the last 35 years has overwhelmingly supported the predictions of Bethe and of Killian [9], President Eisenhower's Science Advisor at that time, that the future did, in fact, belong to improved detection, not improved concealment. Big-hole decoupling reached its zenith in 1960 and has been shown not to be as effective as proponents then claimed. Identification of small seismic events improved greatly as illustrated in Figure 1.

In discussing the "big hole" idea in his role as Science Advisor to the President, Killian [9, pp. 166-167] states "Teller wished to make a dramatic demonstration of the possibilities of cheating, and this was it." Killian goes on to state "the Berkner panel heard Latter's theories about the big hole, and in its report concluded 'that decoupling techniques existed which could reduce the seismic signal by a factor of ten or more.' ..The big-hole technique proved to be much more difficult than expected by its advocates ..It was a bizarre concept, contrived as part of a campaign to oppose any test ban." On page 168 he states "I was asked by the State Department to lead an American technical delegation to London to give the British the information about the 'big hole' and other methods of concealing nuclear tests. ..While we were in London, Dr. Latter said to me in casual conversation that whatever advances might be made in detection technology, the West Coast group led by Teller would find a technical way to circumvent or discredit them."

Finally, on pages 171 and 172 Killian [9] discusses the process of scientific review and advice to the government: "As Henry R. Myers has written , this is true even today. 'There seems to be a widely held obsession with the *possibility* of violations rather than with their probability, or their significance. ..Opponents of limitations on nuclear testing have exploited this obsession by encouraging fears that have little basis in fact.' We should have strengthened the campaign for a test ban by making clear when an apparent technical question in not really technical." .."We who spoke for science never succeeded in making clear the difference between probability and possibility .."

Now that a CTBT is again being negotiated, some of the same arguments are being made again that very large holes can be constructed and used for decoupled explosions as large as 50 kt.

Several exotic schemes have been proposed such as testing in huge cavities in hard rock and in ellipsoidal cavities of large aspect ratio. I believe that a careful reading of the history and politics of decoupling from the period around 1960 is needed to evaluate what is either possible, plausible or bizarre in the context of the debate in the 1990s. Killian's points need to be taken into account in this debate.

3.3 STERLING EXPLOSION, UNCERTAINTIES IN CODE CALCULATIONS AND REVISION OF COWBOY DATA

3.3.1 *U.S. Nuclear Explosions in Salt*

The United States has detonated only three nuclear explosions in salt. The first two, Gnome in New Mexico in 1962 with a yield of 3.4 kt and Salmon in Mississippi in 1964 of 5.3 kt [29], were tamped events. Both of those explosions produced cavities that remained standing for many years, a situation that is almost unique to salt as a geologic testing medium. Cavities produced by tamped nuclear explosions in the common testing medium at NTS, tuff [16], and in hard rock nearly always collapse in a relatively short time. Such cavities, of course, are not then available for use in conducting decoupled explosions.

The Sterling nuclear explosion, a decoupled event of 0.38 kt, was detonated in the Salmon cavity at a depth of 828 m in 1966 to test the decoupling concept. Seismic and other data for the Sterling experiment are described by Springer et al. [30], Healy et al. [31], Denny and Goodman [23] and others. It is the only decoupled U.S. nuclear explosion detonated in domed or bedded salt. Its very small size, however, resulted in a long controversy about the feasibility of conducting larger-yield, clandestine nuclear explosions in much larger cavities in salt and whether such events would be identified or not. Since Gnome and Salmon were both detonated prior to the installation of many high-gain short-period seismic stations and seismic arrays, a long debate ensued about their bodywave magnitudes, m_b, and about m_b-yield relationships for tamped and decoupled nuclear explosions in salt (see Sykes [3] for a longer discussion).

3.3.2 *Code Calculations of DF*

After the tamped Salmon explosion was detonated in Mississippi, but prior to the Sterling event, in 1966, several calculations were made of salt-to-salt decoupling factors for both full and partially decoupled nuclear explosions. Patterson [32-33] and Werth and Randolph [34] report values of DF of 170 for full decoupling in salt using one of the early code calculations, SOC, whereby the entire nuclear explosion sequence was simulated from its initiation through the radiation of elastic waves to large distances . An important set of data used to calibrate these and later code calculations were (and still are) so-called free-field observations that were believed to have been made close to nuclear explosions but in the elastic regime beyond the region of inelastic effects near the shot point.

While Patterson [32] states that observations of that type for the Gnome explosion at a distance of 298 m, which he used in his calculations, may not have been made beyond the elastic radius, it was only realized much later by Denny and Goodman [23], Denny and Johnson [35] and others that peak velocity data for the Gnome and Salmon shots in salt and the Hardhat explosion in granite were probably made in the non-linear strain regime. Likewise, much of the free-field data from the early Shoal and Piledriver nuclear explosions in granite that have been used in calibrating code calculations probably also were made in the non-elastic regime. Rodean [36] remarked in 1981 that calculations made by the SOC73 code used at Livermore do not give "elastic" stress-wave solutions and refers to the calculations as "almost elastic." On page 134 he states "SOC73 solutions for peak particle velocity or peak stress in the inelastic region can be fairly accurate if the stress-strain models are based on measured rock properties. However, SOC73 solutions for stress-wave time histories, particularly at low stress levels in the transition region between inelastic and almost-elastic response, are generally inaccurate if based on measured rock properties. SOC73 can be forced to give a good approximation to observations at a given gauge location in an experimental assembly, but the solutions for other gauge locations will probably be less accurate

and the material properties implied in such forced solutions may be physically unrealistic." "Even if more complete descriptions of material response were incorporated into SOC73, there would still be substantial limitations to the accuracy of the calculated seismic source function for a given explosion. Geological inhomogeneities within the inelastic region of an explosion are more the rule than the exception."

Thus, there are reasons to distrust code calculations of DF at the factor of 2 or 3 level for salt and hard rock as well as predictions of seismic amplitudes at large distances at the factor of 1.5 to 2 level. The utility of code calculations for calculating DF for partial decoupling and for non-spherical cavities is discussed later in Section 11.6. The United States has conducted only three nuclear explosions in granite, all of them several decades ago, and only a few in other hard rocks. Thus, the body of observations from U.S. nuclear explosions in salt and hard rock that can be used to calibrate computer codes is small and is largely confined to older explosions. A greater data base probably exists for explosions in those media in the U.S.S.R. that could be used for better calibration. A potential violator of a CTBT, however, will always be faced with uncertainties in calculating seismic amplitudes and decoupling factors and would need to work conservatively if secrecy is to be maintained and the probability of identification by outside countries kept low.

3.3.3 *Lower Values of DF Estimated by Tucker*

In December 1964 Tucker [37] estimated DF values of 30 to 40 that were much lower than the salt-to-salt values of 100 to 120 reported in 1960 and 1961 for the Cowboy chemical explosions [7, 24, 27] or those of about 170 that were based on early code calculations [32-34]. His DF value of 8 to 12 for a decoupled salt cavity compared to tamped tuff is much smaller than the values of about 300 calculated in 1959 and 1960. As far as I can discern, his paper had little or no impact on test ban negotiations, coming as it did just after the signing of the Limited Test Ban Treaty. Also, his work was discounted as soon as results were available from the 1966 Sterling explosion.

Tucker remarked, however, that chemical explosives like those used in the Cowboy experiments would occupy a volume with a radius of some 25 feet (7.6 m) when scaled to 5 kt. He states "Thus tamped HE [high explosive] shots are really small cavity shots filled with a gas 1000 times heavier than air, producing a pressure profile atypical to that of a point source." He states that cavity calculations made by Patterson in 1964 at Livermore lead to a decoupling factor decreasing importantly with distance to a final value of 43, which agrees well with data from the Cowboy shot he examined. Tucker's work suggests that extrapolations of data for the Cowboy chemical explosives to much large decoupled nuclear explosions should be treated as approximations, especially the estimates of DF.

3.3.4 *Observations of DF for Salmon/Sterling Pair*

Springer et al. [30] obtained a decoupling factor of about 70 at low frequencies by comparing the seismic signals for the Salmon and Sterling explosions. Sterling was detonated in the cavity created by Salmon at a depth of 828 m. DF was obtained from spectral ratios of the two signals at low frequency (about 1000) divided by the ratio of the two yields, 5.3/0.38 = 14. Soon after the Sterling event, several workers attempted to attributed the observed DF of 70 to one of two factors. Firstly, the salt surrounding the Salmon cavity was thought to have been weakened by the initial explosion, leading to a lower DF than that expected for a cavity made by either conventional or solution mining of salt. Secondly, the yield of Sterling was about 1.8 times too large for full decoupling in the Salmon cavity. By that view a larger DF would have been obtained for a 0.2 kt explosion, the yield calculated for full decoupling. In their 1990 review of the data for Salmon and Sterling, Denny and Goodman [23] conclude, however, that the second view was not correct and that DF for full decoupling in an explosion-produced cavity would not be much larger than the value obtained by Springer et al. [30]. The first view remains mute since a decoupled nuclear explosion is not known to have been tested in a cavity in salt created by either conventional or solution mining.

Healy et al. [31] found that DF decreased as a function of frequency for the Salmon-Sterling pair. Blandford [38] calculated a DF of only 7 at 20 Hz., the highest frequency for which reliable

data exist. A significant decrease in DF is expected, however, since the corner frequency for Salmon was lower than 20 Hz while that for Sterling was about 35 Hz [23]. The spectrum of a fully decoupled explosion is expected on scaling grounds to be close to that of a smaller explosion, i.e. lower in its low-frequency level than that of a tamped explosion of the same yield but with a higher corner frequency. Thus, a decoupled explosion with DF = 70 of yield equal to that of a tamped explosion of m_b 4.85 is expected to have a spectrum similar to that of a tamped explosion of $m_b = 4.85 - \log 70 = 3.0$ and a corner frequency like that of a tamped explosion of m_b 3.0.

3.3.5 *Downward Revision of Decoupling Factors for Cowboy Explosions*
About a decade after Sterling and nearly 20 years after Cowboy experiments, it was realized that the decoupling effectiveness for the Cowboy shots had been overestimated [39]. Values of DF for Cowboy were revised downward by a factor of 0.7 to account for new information on the energy release associated with the detonation of the unconfined high explosive, Pelletol, used in the cavity explosions for Cowboy as compared to the energy release of the same explosives when confined, i.e. tamped [39]. This revision brought DF from the Cowboy experiments into agreement with the factor of 70 obtained for Sterling. Most subsequent work in the United States, including the 1988 OTA Report [14], has taken DF to be a factor of 70 for full or nearly full decoupling for salt.

While I use a DF of 70 in the remainder of this paper for either full decoupling or for Sterling conditions, it should be realized that the data from Cowboy and Sterling are meager and the agreement in values of DF may be more fortuitous than real. Sterling was so small that it was not observed beyond 113 km. Thus, estimates of DF are based on seismic waves leaving only a portion of the focal sphere surrounding that event. Data from the much larger, partially decoupled explosion at Azgir of 1976 were recorded at teleseismic distances and sample a greater portion of the focal sphere. Information on that event, which is discussed in section 9.2, has re-opened the subject of decoupling and of estimates of DF for partially decoupled nuclear explosions in salt.

4. Why does Decoupling Work?

The solution of the problem of a radial pressure pulse applied to the interior of a spherical cavity in a homogeneous isotropic elastic medium has been known for many decades and has been used since the first work on decoupling [7]. From that pressure history it is possible to calculate displacements and stresses everywhere in the surrounding medium as a function of time. Crucial to the application of that solution is that the rock surrounding the cavity remain in the elastic strain regime and not be either subjected to inelastic strain or fail in tension. For full decoupling to occur a cavity would have to be excavated with a radius equal to the so-called elastic radius where cavity pressure is low enough that the surrounding medium, in fact, remains in the elastic regime.

Making a cavity larger than the elastic radius does not change the amplitude of the long-period (low-frequency) seismic waves radiated to large distances [7, 39-40]. We can construct an imaginary sphere surrounding a tamped nuclear or chemical explosion such that the pressure (i.e. the radial stress) on it is just small enough to keep the surrounding rock medium entirely in the elastic regime. Decoupling works because the elastic radius of that imaginary sphere is larger than that of an air-filled cavity that is just large enough to fully decouple an explosion of the same yield (and keep the rock medium surrounding the cavity entirely in the elastic regime). Put another way, the pressure at the elastic radius for a tamped explosion is larger than that at the same radial distance from a cavity suitable for full decoupling of an explosion of the same yield. This occurs because the strong shock wave generated by an explosion decays faster in air than in rock [36, 40]. Another way of viewing the decoupling problem is that the amplitudes of long-period seismic waves (which are proportional to the seismic moment) of an explosion are proportional to the amount of new volume created by the event. That change in volume is smaller for a fully decoupled explosion than for a tamped event.

Only a few percent of the energy of an underground nuclear explosion is radiated to large distances even for tamped explosions in rocks like salt and granite that couple energy relatively

efficiently into seismic waves. For tamped explosions most of the energy goes into vaporizing rock (and thus producing a cavity) and into heating and permanently deforming the surrounding rock. It takes only a small increase in the energy absorbed in the inelastic region to alter greatly the amount of energy radiated to large distances as Terhune et al. [41] illustrate. Thus, in the case of a cavity that is suitable for full or nearly full decoupling, a large percentage of the explosion energy goes into the internal energy of the gas in the cavity (and the bomb-produced products and remnants of the device), less is radiated to large distances, and little or none is expended in forming cracks and in other inelastic deformation of the rock surrounding the cavity.

Nevertheless, determining or measuring the elastic radius has proven difficult since inelastic effects continue to occur down to strains smaller than 10^{-6}. It has proven difficult to ascertain very accurately the size of a cavity needed for full decoupling of an explosion of a certain yield in a given rock type. Achieving complete elastic behavior, in fact, probably would involve making a cavity about 5 times larger in volume than the Salmon cavity for an explosion of the yield of Sterling [42]. The much greater expense of making such a cavity and of keeping its construction and use secret would almost certainly not be worth a small to negligible increase in DF compared to the value of 70 obtained for Sterling and Cowboy. Thus, an evader of a CTBT choosing cavity decoupling is more likely to opt for a cavity in salt that is somewhat smaller than that for full decoupling (by the Latter criterion of section 5), i.e. to use a cavity with a radius about that for the conditions of the Sterling explosion, about 23 m times the cube root of the yield.

5. Insuring Containment of Decoupled Nuclear Explosions

The minimum depth for a clandestine test in an underground cavity in salt is determined by the requirement that the explosion not produce a crater or other disturbance at the surface and that it be fully contained so as not to leak radioactive products to the surface. For a very weak material like salt, Latter et al. [7] concluded that the amplitude of the long-term step of pressure on the cavity wall for full decoupling must be less than or equal to one half of the overburden pressure (i.e. half of the vertical stress, ρgh) so as to prevent failure in tension of the surrounding salt material and, hence, to prevent leakage of radioactive gases from the cavity. Since salt, like other geological materials is very weak in tension, a large compressive overburden stress is need to make sure that salt near the cavity wall is not subjected to tensional hoop stresses from either the pressure step or the shock wave of the explosion. The relationship between a step in cavity pressure, P, produced by a decoupled explosion of yield, Y_D, in a cavity of volume, V_C , and the requirement for containment that P be less than some constant, k, times the vertical stress can be written

$$P = (\gamma-1)Y_D/V_C < k\,\rho gh \quad (1)$$

where γ is the ratio of enthalpy to internal energy of the cavity gas, which is taken to be 1.2 for air at atmospheric pressure [7, 36], ρ is the average density of the material from the surface to the depth, h, of the cavity and g is the gravitational acceleration at the earth's surface. The average density used in this paper for decoupling in cavities in salt is taken to be that of salt at the Salmon site, 2200 kg / m^3 [16], which is similar to that reported for the Azgir area in western Kazakhstan [10, 43]. For the Latter criterion mentioned above, k = 0.5. When P is equal to the overburden stress, the so-called Patterson criteria, k = 1.0. The conditions of the Sterling explosion correspond to k = 0.9.

The two groups--Livermore and S-Cubed--that continue to perform code calculations of DF and of various effects of underground nuclear explosions use equations of state for various materials rather than the simple Latter criterion [15-16, 42]. Nonetheless, in their calculations decoupling effects do become important for salt and tuff near the Latter criterion [16]. Of greater importance in those code calculations is the choice of appropriate equations of state for salt and hard rock that

take into account inhomogeneities like joints in the case of hard rocks and the properties of salt *in situ* for cavities created by either nuclear explosions or solution mining.

6. Scaling Relationships for Yield, Volume, Cavity Radius and Seismic Magnitude

For explosions in the same material it is common to scale dimensions such as cavity radius and depth by the cube root of yield and the volume by yield to the first power. The scaled cavity radius is thus the radius / $Y^{1/3}$ and the scaled cavity volume = V_C/Y. Seismic amplitudes at low frequency for tamped explosions at a given testing area typically scale as Y to about the 0.8 power. Since the seismic bodywave magnitude, m_b, is proportional to the log of the P wave amplitude for frequencies near 1 Hz., m_b is typically regressed against logY to obtain expressions like

$$m_b = 4.4250 + 0.832 \log Y \qquad (2)$$

a relationship obtained in section 7 for tamped nuclear explosions in salt in the Pre-Caspian depression. Although tamped explosions at the same depth in a given material and testing area scale as Y to the first power [35], the 0.8 power found in regressions of most data sets results from the fact that explosions of greater yield are detonated at greater depths than most smaller events to insure the containment of larger explosions.

6.1 CAVITY SIZES FOR FULL DECOUPLING IN SALT

Using the Latter criterion, k = 0.5 in Eqn. (1), full decoupling for the 16.7 m radius of the Salmon cavity at a depth of 828 m corresponds to an explosion of Y = 0.21 kt. Scaling to 1 kt gives a radius of 28 m for the same depth. That scale depth is not very different from that obtained by several other authors. An 8 kt fully decoupled explosion would require a radius two times that, 56 m, and a cavity volume 8 times larger. For Sterling conditions (k = 0.9) the radii are 23 and 46 m for 1 and 8 kt.

7. Tamped Nuclear Explosions in Salt in Former Soviet Union

Unlike the United States, the U.S.S.R. has detonated a large number of nuclear explosions in and near thick deposits of salt. These events, most of which were Peaceful Nuclear Explosions (PNEs), took place between 1966 and 1987. In this chapter I examine the locations of those events and magnitude-yield relationships for tamped nuclear explosions in salt.

7.1 LOCATIONS OF NUCLEAR EXPLOSIONS IN SALT DEPOSITS

Figure 2 shows areas of thick salt deposits of the FSU as taken from publications of the U.S. Geological Survey for the purpose of assessing underground nuclear testing, including sites of possible decoupled testing [44-45]. Gaev et al. [46] published a map of the U.S.S.R. showing salt deposits suitable for construction of cavities in salt with emphasis on industrial uses. Their map, which includes many of the deposits of Figure 2, differs in detail in some places from it and includes more widespread salt deposits on the Russian platform to the east of Moscow. Their map probably includes somewhat thinner deposits of bedded salt since its purpose was to indicate opportunities or areas for constructing small cavities for various industrial purposes as well as depicting thicker salt deposits such as salt domes. Rachlin [57] states that the small-scale map of salt areas of the U.S.S.R. of Gaev et al. [46], their Figure 3.2, is "over generalized, and in places extend beyond the limits of known salt deposits, as shown on other maps published by the

Soviets." Fryklund [55] also examined the Soviet literature on salt deposits, especially locations of salt domes that may be suitable for significant decoupled nuclear testing.

Salt domes have also been discovered in the Norwegian and Russian sectors of the Barents Sea [55-56] that are not shown on Figure 2. Sensitive seismic arrays in Norway and Finland indicate that the Barents Sea has a very low rate of natural earthquake activity and no industrial explosions, making it easy to monitor in terms of a CTBT. Those arrays have a coverage down to very small magnitudes, better than 2.5 to 3.0.

Sykes [3] used the locations of various PNEs detonated by the U.S.S.R. to derive a list of 53 nuclear explosions detonated in or within about 200 km of the thick salt deposits of Figure 2. Table 1 of Sykes [3] describes the locations, dates, origin times and bodywave magnitudes, m_b, of those events. Sultanov et al. [12] describe the rock types at the shot points of 116 Soviet PNEs including the partially decoupled explosion at Azgir of 1976 but excluding 6 very small nuclear explosions detonated in a water-filled cavity at Azgir. Sykes discusses the 1976 event and those 6 explosions separately as is done later in section 9.3.

Of the explosions in or near thick salt deposits from the lists of Sultanov et al. [12] and Sykes [3], most occurred to the north of the Caspian Sea within the Pre-Caspian depression, one of the world's largest salt dome provinces. That area contains up to 20 km of sediments and is floored by crust of Devonian age. Speculation differs as to whether that crust is either a remnant of Paleozoic oceanic crust that has not been subducted or consists of deeply buried continental rocks.

Several of the sites of nuclear explosions in the Pre-Caspian region are shown in Figure 3. The largest explosions in salt were detonate near the small town of Azgir in western Kazakhstan between 1966 and 1979. Tamped explosions at Azgir range in yield from 1 to 100 kt [10-11]. Azgir, an area of low population density, appears to have been a major testing ground for the technology and effects of peaceful nuclear explosions [12]. The name for Azgir in Kazakh is Chapchachi.

A series of 15 nuclear explosions with yields of about 3 to 15 kt [3] were denoted near Astrakhan in the adjacent part of the Russian Republic (Figure 3) from 1980 to 1984. Five nuclear explosions were conducted in the general vicinity of Orenburg from 1970 to 1972 and 6 at Karachaganak in two series in 1983 and 1984. The Orenburg, Astrakhan and Karachaganak explosions occurred within major petroleum fields. Refining capacity at those sites was increased after the detonation of the nuclear devices as judged from SPOT and Landsat satellite images and other information [3-4, 47-49]. In those cases the cavities created by nuclear explosions were intended for storage of gas condensates [47-49]. The yields of devices at those three sites were no larger than 15 kt [12, 63], probably to prevent damage to industrial equipment for petroleum extraction and refining and to nearby centers of population. The Azgir area, however, is not a site of petroleum extraction or refining, other industry or population centers larger than villages or collective farms [5, 50].

Without precise knowledge of the depths of explosions and details of the stratigraphy, especially for regions of bedded salt, it is not possible to ascertain whether past tamped nuclear explosions, in fact, occurred in salt or in some other rock type. An example of this is the series of 7 nuclear explosions listed in Table 1 of Sykes [3] that were conducted south of the town of Mirnyy in Yakutia near 61.5^{o}N, 112.8^{o}E within the large region of bedded salt to the north and northwest of Lake Baikal (Figure 2). The yields of those events are not larger than 16 kt [3, 63]. Sultanov et. al [12] indicated that only one of those explosions occurred in salt; the others were conducted in dolomite in conjunction with oil recovery. Likewise, the largest explosion at Azgir was being set off in clay [11-12, 63]. That event at a depth of about 1000 m also resulted in the formation of a large depression at the surface [11].

In calculating the possibility of using cavities created by past nuclear explosions for clandestine nuclear testing under a CTBT, I will use the conservative assumptions that the cavities, in fact, remain standing and that all of the events listed by Sykes [3] as occurring in or near thick salt deposits of the FSU will be treated as if each occurred in salt.

7.2 BODYWAVE MAGNITUDES OF TAMPED EXPLOSIONS IN SALT

Revised bodywave magnitudes, m_b, were recomputed for all known Soviet underground nuclear explosions in the vicinity of Azgir for which data were available from the International Seismological Center (ISC), the U. S. Geological Survey (USGS) and the Norsar and Hagfors seismic arrays in Scandinavia for the period January 1961 through May 1993. Station corrections for Azgir events were derived for the 6 largest explosions at that site using standard methods and then applied to all known explosions at that testing area. Stations used in the recalculations were confined to the distance range 20^o to 95^o. A major object was to reduce the standard error of the mean (SEM) for m_b to values as small as 0.015 to 0.03 by both using large numbers of stations (40 to 70 for the larger events) and applying station corrections, i.e. making a correction for systematic differences in magnitude at individual stations for a given testing area. Since individual stations typically record explosions from a given test site with amplitudes that are consistently either higher or lower than the mean for each explosion, the application of station corrections reduces the standard deviation of individual readings considerably and avoids biases related to the inclusion or exclusion of individual readings from one event to another. It is particularly important to use station corrections since measurements of m_b from the stations of countries like Canada or France that operate large networks were not available for some explosions but were available for others.

Recomputed values of m_b for Azgir explosions, their SEM, and other pertinent data are listed in Table 1 of Sykes [3]. A special study was made of the Azgir explosion of 1.1 kt of 1966 wherein all available WWSSN and Canadian records were searched for the P wave from the event. Using 16 stations, $m_b = 4.524 \pm .056$. (The uncertainty in magnitude is plus or minus one SEM.) Although small in amplitude, P waves could be readily identified at many of the better WWSSN stations of higher gain and good signal-to-noise ratio. The ability to detect such a small event 29 years ago using analog records from mainly simple (non-array) stations reflects the high coupling of a tamped underground explosion in salt and the efficient propagation (high Q) for P waves from the Azgir area to stations worldwide A similar study for the 1968 Azgir PNE event of 25 kt gave $m_b = 5.529 \pm .027$. For both of the two Azgir events, readings were used from only from those stations for which a station correction was available based on the 6 largest events at Azgir. This use of station corrections avoids the largest contributor to biased determinations of m_b for small events, i.e. the inclusion of raw m_b values that are mostly from stations that systematically report larger than average magnitudes, such as those in Scandinavia. For example, m_b values for large Azgir explosions at Norsar are 0.48 ± 0.08 units larger than the event means. Correction for that systematic effect results in subtracting 0.48 from Norsar's raw m_b's.

Since station corrections obtained for explosions at Azgir did not reduce the SEM for events in salt located farther than 100 km away, no station corrections were applied by Sykes [3] in recalculating m_b values for those other events located in or near salt deposits of the FSU. Magnitudes computed without station corrections for events of about $m_b < 5$ are likely to be biased high [51] and the computed yields similarly biased. For the purpose here of estimating the potential to use cavities created by past nuclear explosions for decoupled testing under a CTBT, however, the those biases lead to overestimates of the sizes of decoupled explosions that could be conducted in such cavities, i.e. those not located at Azgir.

7.3 MAGNITUDE-YIELD RELATIONSHIP FOR TAMPED EXPLOSIONS IN PRE-CASPIAN DEPRESSION

The revised values of m_b and the published yields for the Azgir explosions of 1966, 1968 and 1971 and the Orenburg event of 1971, all of which are reported as having been detonated in salt in the Pre-Caspian region (Figure 3), were used to obtain the m_b-yield relationship of Eqn. (2). The yields of the explosions at Azgir in 1966 and 1968 were made public 25 years ago as part of an exchange of data on peaceful uses of nuclear explosions [43]. The 64 kt yield of the Azgir

explosion of 1971 is from Adushkin et al. [10]; the 15 kt value for the 1971 Orenburg event is from Refs. [47, 49, 52]. The three tamped explosions in salt at Azgir have magnitudes similar to those of explosions of similar yield in hard rock in the southwestern portion of the Shagan River testing area in Central Asia (Figure 1) and, once corrected for test site bias, to those of the three U.S. explosions of announced yield in granite in Nevada [2]. Thus, the Azgir events in salt exhibit a coupling of explosion energy into seismic wave energy that is about as efficient as that of explosions in granite and other hard rock. Also, the Azgir area is one of efficient transmission of seismic P waves to large distances. Much of the FSU, especially most of the areas of thick salt deposits, consists of pre-Mesozoic rocks and of upper mantle materials that transmit seismic waves P efficiently. The salt in the Pre-Caspian depression is of Permian age and that in the large area of bedded salt to the northwest of Lake Baikal is of Cambrian age.

As this paper was nearing completion, I was furnished an unpublished list of dates, depths and yields of all Soviet PNEs that was turned over to the U.S. Department of Defense by the Russian Defense Ministry [63]. The yields calculated by Sykes [3] for explosions in salt at Azgir, Astrakhan, Orenburg and Karachaganak are very similar to those on that list. Using those yields for explosions in salt in the Pre-Caspian depression (Figure 3), nearly the same m_b-yield relationship as that in Eqn. (2) is obtained.

7.4 IS SALT A HIGH OR LOW COUPLING TESTING MEDIUM?

Most workers who have studied the seismic waves from underground nuclear explosions in thick deposits of salt (e. g. SIPRI Seismic Study Group [21], Marshall et al. [53], Rodean [36]) conclude that salt is one of the best-coupling, common geologic media, i. e. that tamped explosions of a given yield in salt have among the largest bodywave magnitudes. The large values of m_b in Figure 1 for Azgir explosions support that contention. This is reasonable since salt has a low porosity. Relatively little of the energy of the explosion must be expended in closing pore space, especially air-filled pore space, as is the case with explosions conducted above the water table in less competent sedimentary rocks such as alluvium.

Based on their determination of the m_b of Salmon, Blandford et al. [54], however, conclude that its magnitude, when corrected for bias between testing areas, was 0.4 m_b units below the magnitude-yield curve for shots in volcanic and granitic rocks in Nevada, Amchitka and Algeria. They conclude from that single data point for Salmon that explosions in salt couple less well than those in hard rock. The data from small and large explosions in salt at Azgir, however, do not support their contention. It should be remembered that the seismic data for the nuclear explosions at Azgir and for other Soviet events in salt were recorded by more stations, especially arrays, than the two U.S. tamped explosions in salt--Gnome and Salmon--which occurred more than 30 years ago. Sykes [3] describes problems of determining m_b for Salmon in more detail.

Marshall et al. [53] calculated a magnitude and SEM for Salmon of 4.87 ± 0.08 using data from 11 stations at distances, Δ, greater than 20^o. When that m_b value is corrected for the relative attenuation between the Salmon and Azgir testing areas using the data and formulas of Der et al. [58], $m_b = 4.90$ is obtained. Using that m_b, a yield of 3.7 kt is derived from Eqn (2), which is only somewhat smaller than the announced yield, 5.3 kt. Thus, the calibration data from Azgir explosions are consistent with an m_b for Salmon near 4.9, i.e. in the range quoted by the SIPRI Seismic Study Group [21] in 1968. Not much can be done in utilizing the data from the Gnome explosion of 1962 since Marshall et al. [53] report only two m_b's for $\Delta > 20^o$. The bias in m_b for the Gnome area with respect to other testing areas is also poorly known.

8. m_b-Yield Relationships for Coupled and Decoupled Explosions in Salt

Eqn. (2), the magnitude-yield relationship for tamped nuclear explosions in salt at Azgir and Orenburg, implies that fully-coupled (tamped) nuclear explosions of 1 and 10 kt in salt in those and

similar high-Q areas of the FSU have m_b's of 4.42 and 5.26 respectively. For purposes of calculating magnitudes of fully decoupled explosions I assume DF = 70. Subtracting log 70 from Eqn. (2) gives

$$m_b = 2.58 + 0.832 \log Y. \quad (3)$$

for fully decoupled explosions in salt at Azgir and other high-Q areas of the FSU:

Assuming that attenuation of P waves leaving the high Q (efficient transmission) Azgir site is the same as that for other high-Q areas of the FSU, fully decoupled events of 1 and 10 kt would have m_b's of 2.58 and 3.41 respectively. Most areas of thick salt deposits in the former U.S.S.R. are typified by high Q for P waves and low natural seismic activity. These magnitudes are higher than many previous workers have thought for fully decoupled nuclear explosions in salt. For example, Murphy et al. [40] state "Cavity decoupled underground nuclear explosions in the yield range from 1 to 10 kt can be expected to generate seismic signals corresponding to m_b values in the 2.0 to 3.0 range . . " One of the smallest magnitudes estimated is that of Werth and Randolph [34] who concluded that a 5-kt, fully decoupled explosion would be down in amplitude from that of Salmon by a DF of 170 and have a magnitude of 2.1. Eqn. (3) gives $m_b = 3.16$ for 5 kt fully decoupled, a full magnitude larger than their estimate. Their low estimate arises at least in part from using $m_b = 4.35$) for Salmon as determined from stations as close as 16^o and too large a DF.

8.1 REVISITING THE ORIGINAL DECOUPLING FACTOR OF 300

The salt-to-tuff decoupling factor of 300 that was frequently cited in the period 1959 to 1966 is now mainly an historic curiosity since information on the performance of networks can be tied to explosions other than the single Rainier event of 1957. Nevertheless, a salt-to-tuff DF = 19.5 is obtained by subtracting $m_b = 4.06$ reported by Romney [27] in 1960 (page 89) for the Rainier explosion in tuff in Nevada and $m_b = 2.77$ from Eqn. (3) for a fully decoupled event of the same yield, 1.7 kt, at Azgir. Hence, the decoupling factor of 300 estimated in the early days of the decoupling concept is 15 times larger than that obtained from explosions in salt at Azgir.

Why was the tuff-to-salt DF of 300 overestimated by such a large amount? The three main factors are 1) failure in 1960 to appreciate the large magnitude bias between Nevada and the many regions of efficient transmission of P waves in the U.S.S.R., 2) the more efficient coupling of energy into seismic waves for explosions in salt compared to those in tuff, and 3) failure to consider differences in the rheology of large volumes of rock *in situ* compared to those for intact small laboratory samples.

9. Cavities Formed by Nuclear Explosions in Thick Salt Deposits of FSU that Might Be Usable for Clandestine Testing

9.1 INVENTORY OF PAST NUCLEAR EXPLOSIONS IN AND NEAR THICK SALT DEPOSITS

Many investigators evaluating the possibility of decoupled nuclear testing that might be conducted under either a CTBT have paid considerable attention to the potential use of cavities produced by past tamped nuclear explosions in salt. I now estimate the maximum yields of fully decoupled nuclear explosions that could be detonated in cavities created by past Soviet nuclear explosions detonated either in or near thick salt deposits. I will show, however, that monitoring of the relatively few areas of the FSU in which cavities of that type could exist and might be used in the future for the full decoupling of explosions with yields larger than 0.5 kt is tractable, given both a problem-solving approach and the inclusion of reasonable verification measures in a treaty to further limit nuclear testing.

Yields, depths and cavity dimensions of explosions in salt at Azgir in 1966, 1968 and 1971 and at Orenburg in 1971 have been published by Kedrovskiy [43], Izraehl' and Grechushkina [52] and

Adushkin et al. [10] as have the yields, depths and rock types for a number of underground nuclear explosions at the eastern Kazakhstan test site [59]. The explosions at Azgir listed in Table 1 of Sykes [3] have calculated yields between 1.3 and 93 kt. That range is in good agreement with the statement by Adushkin et al. [10] that tamped nuclear explosions at Azgir were in the yield range from 1 to 100 kt, the reported yield of 1.1 kt [43] for the 1966 explosion and the recent list of yields of Soviet PNEs [63].

The yields, Y(mb), of all of the events in Table 1 of Sykes were calculated from Eqn. (2) assuming that all of them were tamped explosions and that all occurred in salt in areas of low attenuation for P waves. Two conservative assumptions are made in ascertaining potential sites where decoupled tests might be performed in the future. One is that all of those events, in fact, occurred in thick deposits of salt. Sultanov et. al [12] state that several of the explosions in Table 1 of Sykes [3], however, were detonated in either anhydrite, clay, or dolomite and not in salt. Another conservative assumption is that cavities have remained standing for all of the events and that water present in any of them can be removed so that decoupled testing would be possible. Kedrovskiy [43] mentions that the small cavity created by the 1966 explosion at Azgir filled with water. Krivokhastshiy et al. [11] state that 5 of the 9 cavities at Azgir have filled with brine from aquifers at a depth of 200 m. The water in those 5 cavities would have to be pumped out before they be used for decoupled testing.

9.1.1 *Cavity Volume as a Function of Yield and Depth for Tamped Explosions in Salt*
Information about the depths and dimensions of the cavities created in salt by the U.S. explosions Salmon and Gnome, three explosions at Azgir and one near Orenburg are used to calculate yields of fully decoupled nuclear explosions that could be conducted in the cavities assumed to remain standing from the events in Table 1 of Sykes [3]. None of those cavities was perfectly spherical in shape. In each case a significant amount of rubble, radioactive products and re-solidified salt accumulated at the bottom of what was initially a more nearly spherically-shaped cavity. In the following descriptions and calculations the cavity volume, V_C , referred to is the remaining volume; it does not include the rubble zone since it is the remaining air-filled volume that is pertinent to the conduct of possible decoupled nuclear tests.

Salmon, a fully-tamped explosion of 5.3 kt, was detonated in a salt dome in the state of Mississippi at a depth of 828 m in 1964. V_C of its cavity (in which the Sterling event was detonated) was 19,400 m^3, giving a mean radius of 16.7 m [23]. The Gnome explosion of 1962 was conducted in bedded salt in New Mexico at a depth of 361 m and produced a V_C of 27,400 m^3 [29]. The 1968 Azgir event of 25 kt was detonated at a depth of 590 m and produced a cavity with a volume of 140,000 m^3, giving a mean radius of 32.2 m [43]. The Soviet explosion at Orenburg of October 22, 1971 of 15 kt in bedded salt was used to produce a cavity for storing gas condensates at depth of 1140 m. Its volume was 50,000 m^3, giving a mean radius of 22.9 m [47, 49, 52]. The 1971 Azgir explosion of 64 kt was detonated at a depth of 987 m and produced an air-filled cavity with a volume of about 214,000 m^3 [10] and a mean radius of 37 m. That cavity was used to conduct the partially decoupled nuclear explosion of March 1976 [10]. The 1966 Azgir explosion of 1.1 kt was detonated at a depth of about 165 m and generated a cavity with a volume of 10,000 m^3 with a mean radius of 13.4 m [43]. Although yields and depths of Soviet PNEs have recently been released [63], it does not contain information on cavity sizes.

9.1.2 *Maximum Fully Decoupled Yields Possible for Various Cavities*
Taking the relevant parameters for the cavities created by the Gnome, Salmon, Orenburg and the 1966, 1968 and 1971 Azgir explosions, the maximum yields of fully decoupled explosions according to the Latter criterion (k = 0.5 in Eqn. 1) that could be detonated in those cavities (after converting the energy in Joules, J, to kilotons, where 1 kt = 4.184 x 10^{12} J) are 0.13, 0.21, 0.75, 0.02, 1.1 and 2.7 kt respectively. The ratio, Y_{FD}/Y, of the yield of the largest fully decoupled event that could be detonated in each of those cavities to the yield of the tamped nuclear explosion that was used to create those cavities is 1/26, 1/26, 1/20.4, 1/53, 1/24 and 1/24 for the above 6

events respectively (Figure 4, top). Larger values of Y_{FD}/Y are obtained at deeper depths. That ratio, however, does not increase much between 360 and 1140 m.

Figure 4 shows the scaled cavity volume, V_C/Y, as a function of depth for the above 6 tamped explosions in salt. V_C/Y clearly decreases with depth. There is a tradeoff, however, between the fact that a shallower tamped explosion produces a larger cavity than a deeper one in the same material and the fact that a larger cavity is needed at a shallower depth to satisfy Eqn. (1) for a decoupled event of yield, Y_{FD}. The slow increase of Y_{FD}/Y with depth, h, at the top of Figure 4 can be understood as follows. The data in the lower half of Figure 4 (not including that for the 1971 explosion, which were not available when the calculation was first made) were best fit with regressions of form $V_C/Y \sim h^{-n}$. For the solid line, which includes the data point for the small shallow event of 1966, n = 0.57. When that data point is excluded (dashed line), n = 0.83. Given the yield of a tamped explosion, Y, and h, Eqn. (1) can be rewritten

$$Y_{FD} \leq k\rho g h V_c / (\gamma - 1) \sim Y h^{1-n} \quad (4)$$

where 1-n is 0.43 with and 0.17 without using data from the 1966 event. Thus, for a given yield, Y, of a tamped explosion in salt, the yield, Y_{FD} of a fully decoupled explosion that can be detonated in its cavity, increases slowly with the depth of the tamped explosion.

The cavity dimensions of most of the Soviet explosions in or near salt deposits from Table 1 of Sykes [3] are not known. Assuming that they occurred at the depth of the deepest known nuclear explosion in salt in Figure 4 and taking the ratio of $Y_{FD}/Y = 1/20$, however, should lead to conservative estimates of Y_{FD}.

Thus, much larger (20 to 55 times larger) tamped explosions are needed to create cavities than the maximum sizes of fully decoupled explosions that can be detonated in them according to the Latter criterion (k=0.5 in Eqn. 1). For Sterling conditions (k=0.9) that ratio is 12 to 31. This ratio is important since unclassified data alone are sufficient to identify down to a small yield all past Soviet and U.S. underground nuclear explosions that were detonated either in or near areas of thick salt deposits or in other areas that conceivably could be the sites of such deposits. The yields of fully decoupled explosions that could be detonated in cavities that may remain standing from those events according to the Latter criterion is at least a factor of 20 smaller than the yields of the explosions that generated those cavities. For Sterling conditions, the yield must be at least 12 times smaller.

9.1.3 *Inventory of Cavities Suitable for Full Decoupling by Region and Yield in FSU*

Of the 53 nuclear explosions listed by Sykes [3] as occurring in or near thick deposits of salt of the U.S.S.R., 24 have cavities that may remain standing for which $Y_{FD} \geq 0.5$ kt. Table 1 summarizes the yields of those 24 events by area and maximum yield, Y_{FD}. Most of the possible locations (22 of 24) for such testing are concentrated in the area to the north of the Caspian Sea in the Pre-Caspian depression (Figure 3). The possibilities for conducting larger tests, up to a maximum of 4.2 kt fully decoupled, are mostly confined to Azgir itself. Possibilities for decoupled testing in cavities created by past nuclear explosions within the area of bedded salt to the north and northwest of Lake Baikal are few and the yields very small. Sultanov et al. [12] list only a single small nuclear explosion in salt in that area. The maximum yields of decoupled explosions that could be conducted in those cavities assuming Sterling conditions instead of the Latter criterion (k = 0.9 instead of 0.5 in Eqn. 1) can be obtained by multiplying the values of Y_{FD} in Table 1 or in Table 1 of Sykes [3] by 1.8.

The Bukhara II event of May 1968 was used to put out a fire in a gas well, the drilling of which had encountered an unanticipated fault that had provided pathways for escaping petroleum [43, 47]. It was detonated at a depth of 2440 m near the boundary between anhydrite and salt [43, 47]. The great depth of the Bukhara II explosion insures that any cavity that may have been created undoubtedly closed by plastic deformation of salt soon after detonation, as, in fact, was the intention in putting out the gas fire. The presence of a fault known to have leaked in the past

would make the conduct of a decoupled nuclear test at that site a risky proposition even if a cavity does remain standing. That site in Central Asia is now located in a separate republic, not the Russian Republic.

Two explosions of 1972 in Table 1 to the northeast of Elista and at Lake Aralsor were situated along an 800-km long deep seismic sounding profile for which a cross section is reproduced in Scheimer and Borg [60]. The cross section indicates that salt is only present at a depth exceeding several kilometers for the first explosion and is absent altogether near the second. This is in accord with the statement of Sultanov et al. [12] that the Lake Aralsor and Elista explosions were conducted in clay and with that by Bogacheva et al. [61] that the 6800 m deep Aralsor borehole (which was located at or near the shotpoint of the first explosion) penetrated a complete Triassic sequence of rocks that are undisturbed by salt tectonics, i.e. by the presence of salt diapirism. The yields calculated by Sykes [3] for those two explosions in clay are among the few in that list that are much larger than those recently provided by the Russian Ministry of Defense. Those smaller yields are in accord with the statement of Sultanov et al. [12] that coupling is even more efficient in wet clay than in salt.

If the statements about the events that were detonated in clay are correct, all of the cavities that may remain standing from past nuclear explosions in salt that could be used for full decoupling of explosions of $Y_{FD} > 1$ kt are situated at Azgir. If that is the case, the monitoring of such cavities by a combination of a local seismic network, satellite and air photography and on site inspections would be very easy if provisions to that effect are included in a CTBT. In any case, it would not be much more difficult in a monitoring program agreed to by treaty to include the sites of the other past large nuclear explosions in Table 1 for which the events are reported to have been detonated in clay.

Thus, the number of cavities produced by past nuclear explosions in the FSU that potentially could be used for clandestine testing of fully or nearly fully decoupled nuclear explosions under a CTBT is very limited. Those sites are confined to a few areas of the former U.S.S.R. Most, and perhaps all, of the larger cavities produced by nuclear explosions that may remain standing are situated in the Republic of Kazakhstan and not in the Russian Republic. One small nuclear explosion in salt with a yield of about 4 kt was detonated in the Ukraine at a depth of 2483 m [3, 12, 63].

9.2 PARTIALLY DECOUPLED NUCLEAR EXPLOSION AT AZGIR IN 1976

Recently released information on the Russian program of nuclear explosions conducted at Azgir [10-12] indicates that a partially decoupled test of about 8 to 10 kt was detonated on March 29, 1976 within the air-filled cavity created in a salt dome by a tamped nuclear explosion of 64 kt on December 22, 1971. The 1976 event was more than 20 times larger than Sterling, the only U.S. decoupled nuclear explosions detonated in salt. The Azgir explosion was recorded not only at local distances, like Sterling, but also at regional and teleseismic distances. Its large size relative to Sterling and the fact that it is the only known Russian decoupled nuclear explosion makes it of great importance in assessing decoupling scenarios, especially those involving yields of 1 to 10 kt.

As stated in Section 7.2 station corrections were derived for the magnitudes, m_b, of 6 largest explosions at Azgir (including the 1971 event) and applied them to all known events in the Azgir region including 10 tamped explosions from 1966 to 1979, the partially decoupled event of 1976 and 6 very small nuclear explosions detonated in a water-filled cavity that are described in section 9.3. The revised m_b's of the 1971 and 1976 events are 6.06 ± 0.02 and 4.06 ± 0.04. The 1976 value is based on data from Norsar (with its station correction of 0.48 m_b units applied) and 6 standard stations of the Soviet network (Table 2). Amplitudes, a, used in calculating the m_b's and the decoupling factor (DF) were restricted to the narrow period range 0.6 to 1.1 s and include data from stations at distances from 785 to 4310 km. The 1976 event was recorded by at least 15 stations in Eurasia. The m_b's of those 6 Soviet stations were computed by subtracting the log of the amplitude ratio a^{71}/a^{76} from $m_b = 6.06$ for the 1971 event. The periods of observation of the two explosions were close enough that the amplitude ratio can be compared directly in computing

m_b for the 1976 explosion. These procedures for Norsar and the 6 Soviet stations insure that m_b is not biased high for the smaller event.

Assuming the amplitudes used in Table 2 for the 1971 event with an average period of 0.73 s pertain to the flat, low-frequency portion of its source spectrum, DF = 12 is obtained for the 1976 explosion for B = 1.0 in the formula for DF in Table 2 using yields of 64 and 8 kt [10] for the 1971 and 1976 events. There is general agreement that low-frequency amplitudes scale as yield to the first power, i. e. B = 1.0, for explosions at the same depth [35], as was the case for the 1971 and 1976 events. It seems unlikely that the amplitudes used in Table 2 for the 1971 event were made close to a minimum in the spectrum since analysts tend to pick the largest amplitude rather than the smallest in the vicinity of 1 Hz in determining m_b for teleseismic P waves. Also, the m_b of 6.06 for the 1971 explosion is already unusually large for events anywhere of yield near 64 kt (Figures 1 and 5). The measured amplitudes for the 1976 event at an average period of 0.93 s are undoubtedly located on the flat portion of its spectrum as would be that of a tamped event of similar yield. From Eqn. (2) a tamped event of Y = 8 kt is predicted to have $m_b = 5.18$. Subtracting $m_b = 4.06$ for the 1976 event from 5.18 gives DF = 13, in close agreement with DF = 12 obtained above.

The relatively small value of DF (compared to 70) and the fact that an explosion of 8 kt exceeds the Latter criterion by about 8/2.7 = 2.95 times indicate that the 1976 explosion was only partially decoupled. This is also so if the yield were somewhat larger.

9.2.1 *Yield of the 1976 Explosion*

Glen and Goldstein [42] report a 1993 personal (oral) communication with V. B. Adamski that the yield of the 1976 explosion was 11.5 kt based on radiochemical analysis, not 8 kt as given by Adushkin et al. [10]. Sultanov (oral communication to Sykes, 1993) described the device used in the 1976 experiment as a standard one whose yield was determined by hydrodynamic methods. Glen and Goldstein [42] use the larger yield stating that the hydrodynamic method would not be as accurate for an explosion in a large cavity. What is not clear is whether the hydrodynamic method was, in fact, used for the actual device detonated in 1976 or instead was employed earlier in the development of the standard nuclear explosive in a conventional tamped testing mode.

Support for a yield of about 8 kt comes from estimated yields of several of the Astrakhan explosions, which are between 7 and 9 kt, indicating that they may be the same standard device used in applications of PNEs that was used at Azgir in 1976. Figure I.2 of Sultanov et al. [12] gives scaled [relative] yields of Soviet underground nuclear explosions in salt as a function of ISC magnitude. Six events cluster near the same yield on their figure. Calibration of their scale using Eqn. (2) indicates that those 6 events also had a yield about 7 kt. They also state that 5 of the 6 explosions they describe at Astrakhan and 3 PNEs conducted in granite had the same yield. The average yield of those 5 Astrakhan explosions as determined by Sykes [3] is 8.8 kt. The yields of many Soviet PNEs at Astrakhan and in other areas of the FSU in the list recently furnished by the Russian Defense Ministry is 8.5 kt [63]. In fact, none of yields of the 124 events on that list was 11.5 kt and none were 11 or 12 kt. Thus, there are grounds for thinking the 1976 event at Azgir, in fact, had a yield of 8 to 9 kt, not 11.5.

Two other recent Russian lists give estimates of the yield of the 1976 explosion. In a report on radiation conditions in the Azgir area Krivokhatshiy et al. [11] give the yield as less than 10 kt. An unpublished list of yields of Soviet PNEs furnished to the U.S. Defense Department in 1994 [63] gives 10 kt. An early abstract of the Adushkin et al. [10] paper submitted to a meeting in 1992 gives the yield as 9 kt. Of the various yields of the 1976 explosion that of Adushkin et al. [10], 8 kt, and Krivokhatshiy et al. [11], less than 10 kt, are contained in published journals. The others are an oral communication in the case of the 11.5 kt value or written but unpublished communications in the other two cases.

In their 1994 paper Glen and Goldstein [42] indicate no uncertainty about the 11.5 kt yield. In an addendum to their 1993 paper on much the same material, however, Goldstein and Glen [62] state that they learned on April 27, 1993 from Adamskii "that the yield of the decoupled explosion (AIII-2) **may have been 11.5 kt**" [emphasis added]. Thus, the portrayal of 11.5 kt as the best

determination of the yield of the 1976 event by Glen and Goldstein [42] and in the Issue Paper by the Defense Nuclear Agency [19] should not be accepted uncritically as fact. The uncertainty about the yield of the 1976 explosion is likely to remain unless more information becomes available. It is possible, however, that not enough information exists to reduce the present uncertainty. While I use 8 kt in Figures 5 and 6, a nominal yield of say 10 kt may be appropriate in assessing decoupling potentials. In that case DF = 15.4.

One historical note on the 1971 and 1976 Azgir explosions is worth mentioning. *Newsweek* magazine for May 10, 1976 in a story on page 4 called "Fooling a Seismograph" states that U.S. experts monitoring Soviet nuclear tests suspect that Russia is using a new trick called decoupling to mask the strength of underground explosions by setting them off in large subterranean caverns created by nuclear tests. They declare that a test carried out in March [1976], for instance, was rated at 2 kt and that a previous test at the same site had been measured at 210 kt. They go on to state that U.S. engineers, suspecting decoupling upgraded the original rating [of 2 kt] to 40-50 kilotons. While one cannot be sure of the source and correctness of this information, the story is clearly full of detailed technical information that a reporter is unlikely to make up. The events are clearly the 1976 and 1971 explosions at Azgir. The information given is consistent with yields at that time being calculated without a correction for m_b bias with respect to Nevada [14,]. Making a correction of 0.32 m_b units [3, 58] gives yields of about 0.4 and 84 kt assuming both events were tamped, in good agreement with yields calculated in the same way from Eqn. (2) and the m_b's of 4.06 and 6.06 used in this paper. Even when corrected for m_b bias, however, the reported decoupled yield of the March 1976 event would still be too large by a factor of about two. Those who believed the information in the *Newsweek* article clearly obtained the impression that the U.S.S.R. was capable of conducting a decoupled test of 40 to 50 kt, not as we now know a partially decoupled test of about 8 to 10 kt.

9.2.2 *Scaling of Data for 1976 Explosion to 1 and 10 kt Fully Decoupled*

If the magnitude of the 1976 explosion is taken to be 4.06 and its yield, Y, either 8, 10 or 11.5 kt, DF can be calculated from the ratio of the seismic amplitudes in Table 2 divided by the appropriate yield ratio (64 kt/Y). For full decoupling (i.e. DF = 70) m_b can be calculated for that yield as well as for full decoupling at the same depth, about 1000 m, for yields of 1 and 10 kt. Since the depth is taken to be constant, B = 1.0 is the appropriate parameter to use in those calculations. In each case m_b = 2.40 and 3.40 are obtained for 1 and 10 kt full decoupled regardless of the exact yield of the 1976 event. It is understandable the value for 1 kt is somewhat smaller than that obtained from Eqn. (3), m_b = 2.58, since it pertains to a depth of about 1000 m rather than a scaled depth for tamped explosions. The two estimates for 10 kt, however, are almost identical.

Stevens et al. [16] used a finite difference computer code to calculate decoupling factors for explosions in cavities in salt. They conclude, taking an identification threshold of m_b 3.5 as described in the 1988 OTA Report [14] and shown in Figured 1, that "decoupled explosions with yields on the order of 20 to 30 kt could evade identification, even if it were only possible to construct a cavity large enough to fully decouple 5-kt." Their calculations, however, predict a DF of about 55 and an m_b of about 3.3 for the parameters of the 1976 event and a yield of 8 kt (star in Figure 5 interpolated from their 3 curves for explosions in cavities). Their predicted m_b is about 0.75 units below that determined for the 1976 event for 8 kt, 0.65 for 10 kt and 0.6 for 11.5 kt.

9.2.3 *Comparison of Data and Code Calculations*

Figure 6 shows the low-frequency decoupling factor, DF, as a function of the yield, Y, of partially decoupled explosions divided by the yield, Y_L calculated by the Latter criterion (k = 0.5 in Eqn. 1). Calculations of DF by Patterson [32] in 1966 for partially decoupled events are clearly well above the data points for the Azgir and Sterling nuclear explosions and for the Cowboy chemical explosions. While constraining their calculations to nearly fit the Sterling datum, Stevens et al. [16] predict much larger DF for the 1976 Azgir event. This is true for that explosion whether its yield was 8, 10 or 11.5 kt. Murphy et al. [17] reached a similar conclusion about the failure of their code calculations to match the data for the 1976 explosion.

Three sets of calculations of the spectral ratios for the 1971 and 1976 explosions have been made for data collected by temporary stations at distances of 1 to 113 km. Adushkin et al. [10] obtained an amplitude DF of about 20 for the 1976 shot using a yield of 8 kt. The value of B that they used, 0.8, however, is appropriate to explosions of various sizes fired at or near a given scale depth, such as the tamped explosions at Azgir that they used in deriving their value of B. (The data in Table 2 give a very similar value, DF = 18.6, to theirs for B = 0.8 and Y = 8 kt.) Saikia et al. [64] obtained DF = 15 using surface waves at two of those local stations for Y = 8 kt and B = 1.0. Glen and Goldstein [42] obtained an average spectral ratio for the 1971 and 1976 explosions from 7 of the local stations that is about 1.5 times that obtained in Table 2 for stations at greater distances. Glen and Goldstein then computed DF = 27 for Y = 11.5 kt. They then computed DF as a function of the scaled radius for the depth of the Azgir explosion for a salt model with strain hardening. They concluded that their calculations agree with the data from both the Sterling and 1976 Azgir explosions. The issue paper by the Defense Nuclear Agency [19] uses the Glen and Goldstein findings to argue as well that calculations of DF for salt agree with observations.

Agreement is only obtained by Glen and Goldstein, however, when they use their own spectral ratios from local stations and a yield of 11.5 kt. In addition, the data from the local stations scatter considerably when spectral ratios are formed for the 1971 and 1976 events. Saikia et al. [64] would have obtained DF = 21.6 from the local stations they used if they had taken the yield to be 11.5 instead of 8 kt. The data used in all of the calculations of spectral ratios for the local stations were hand digitized. In contrast, the data from more distant stations (Table 2) exhibit less scatter and give DF = 17.7 for Y = 11.5 kt. The latter two values of DF fall below the calculated value of 30 of Glen and Goldstein.

Stations at the distances used in Table 2 are more likely to be employed in monitoring a CTBT than one's from 1 to 113 km. Hence, that reason as well as the smaller scatter of the amplitude ratios obtained from stations at greater distances argue that the smaller value, DF = 12 is to be preferred. The code calculations of Glen and Goldstein [42], Patterson [32] and Stevens et al. [16] give decoupling factors that are too high for salt, especially when data from the more distant stations are considered. In addition, the three sets of code calculations do not agree among themselves for the parameters of the 1976 explosion.

9.3 SMALL NUCLEAR EXPLOSIONS IN WATER-FILLED CAVITY AT AZGIR

The Norsar and Hagfors arrays and the ISC Bulletin have each located a number of small events in the general vicinity of Azgir, including the partially decoupled explosion of 1976. The Norsar, Hagfors and Lasa arrays recorded seismic waves from large events at Azgir that have m_b's about 0.5 units above the average. Thus, those arrays have (or for Lasa had) a detection capability for Azgir that extends down to a very small m_b and yield. The location capability of those arrays by themselves, however, is poor compared with that of either a local seismic network or data from several arrays well distributed in azimuth. Either of those can be obtained by the installation of appropriate seismic monitoring equipment. Ringdal [80] examined first and secondary P arrivals of 5 of the small events near Azgir that are listed in Table 3. He concluded that the March 1976 explosion was detonated about 12 km farther from Norsar than the other 4, which occurred at the same epicentral distance. His findings are in accord with the relative locations of the cavities created by the 1971 and 1968 explosions [5], the reported sites of the 1976 and the other small nuclear explosions at Azgir [11, 12, 43, 63].

Sykes and Lyubomirskiy [6] reported that 7 small events of m_b 3.02 to 4.45 from their catalog of small events in the Azgir region fulfill an origin-time criterion (being detonated exactly on the hour within the uncertainty in estimating origin time) for being either very small tamped or small decoupled nuclear explosions, one of which is the partially decoupled event of 1976. D.D. Sultanov (personal communication, 1993) stated to me that besides the partially decoupled event of 1976 that four of the other events on the list of Sykes and Lyubomirskiy were very small nuclear explosions detonated in a water-filled cavity of radius 32 m that was created in salt by a previous nuclear explosion. The earliest date of those small explosions, 1975, and the description of a

cavity of that radius created by a 25 kt explosion in salt by Kedrovskiy [43] indicate that the small explosions must have been detonated in the cavity created by the 1968 explosion at Azgir. Sultanov indicated that two of the events on the list were not nuclear explosions but stated that two yet smaller nuclear explosions that were not on the list had been detonated in the same water-filled cavity on October 30, 1977 and November 30, 1978.

Since nearly all known or inferred Soviet nuclear explosions at Azgir and in the rest of the Pre-Caspian depression were detonated on the hour in a narrow range of local times from 0600 to 1100 (Figure 7), I asked Dr. Frode Ringdal to search on the Norsar recordings for possible small signals on those dates in 1977 and 1978 that would have been detonated exactly on the hour during that five-hour time window. He reported that the Hagfors array in Sweden did report P arrivals that were consistent to within a few seconds of events having occurred at Azgir on those two dates at 0700 and 0800 GMT respectively. Norsar, however, was not operational at either of the two expected arrival times.

Table 3 gives the dates, origin times, m_b's and calculated yields of the 6 events in the water-filled cavity and the partially decoupled explosion of 1976. Hagfors recorded all 7 events; Norsar recorded 5 and undoubtedly would have recorded and located the other two if that array had been in operation. Station corrections for Norsar and Hagfors (and other stations that recorded the explosions of 1975, 1976 and 1979) were used in deriving magnitudes of the 7 events in Table 3. Eqn. (2) was used to derive approximate yields of the 6 events fired in the water-filled cavity. Apparently the small explosions were tested to see if the fundamental frequency of a water-filled cavity surrounded by salt could be excited so as to produce larger than normal seismic waves near that frequency for use in deep seismic sounding. A simple calculation gives a fundamental resonance of about 11.7 Hz for a water-filled cavity of 32 m radius surrounded by material (salt) of much higher impedance. Murphy et al. [13] report amplitudes up to 5 times those of tamped explosions in salt at frequencies of 7 to 9 Hz. Thus, the 6 events in the water-filled cavity at Azgir were not tests of decoupling but of *enhanced* coupling at certain frequencies commonly recorded in deep seismic sounding. Krivokhatshiy et al. [11] report that the experiments in the water-filled cavity were used to attempt to produce super-heavy elements.

It can be seen that the calculated yields of the three smallest events in Table 3 are 0.01 to 0.02 kt. Since Table 3 was prepared, a list of Soviet PNEs furnished by the Russian Defense Ministry [63] gives the same dates and origin times for the 6 explosions in the water-filled cavity and similar yields, 0.01 to 0.5 kt. Thus, all 7 nuclear explosions in cavities at Azgir were recorded by unclassified array stations. This indicates a very good capability for Norsar and Hagfors to record both very small nuclear explosions and small decoupled events from that region. For DF = 70 the capability is at least as good as 0.7 kt.

Murphy and Barker [65] studies Norsar digital records of the 1976 partially decoupled explosion, three events in the water-filled cavity (14 Oct. 1977, 12 Sept. 1978 and 10 Jan. 1979) and 8 chemical explosions within a few hundred kilometers of Azgir. The first two cycles of the P waves of the 4 nuclear explosions are almost identical and exhibit clear compressional first motion followed a half a cycle later by a larger dilatation. This is so even for the smallest nuclear explosion of the four (0.08 kt on the Russian list [63] and 0.02 kt in Table 3). Most of the chemical explosions, however, have more complex signals in the time domain and indistinct first motions, indicating that most or all of them probably were ripple fired. Thus, a fully decoupled nuclear explosion at Azgir of a few kilotons or larger would be identifiable as such from the character of the first two cycles of its P wave. Making a more confused signal would require setting off a large ripple-fired nearby chemical explosion at nearly the same time. As described in a later section, chemical explosions of sufficient size to mask such a decoupled event are very rare within about 150 km of Azgir. The occurrence of a very large chemical explosion in that or other salt dome areas of the FSU would probably trigger a request for an on site inspection.

10. Stability of Air-Filled Cavities in Salt

It should be appreciated that fully decoupled and partially decoupled nuclear explosions of a few kilotons and larger in salt would have to be conducted within a fairly narrow range of depths. An upper limit will be set by containment criteria, i. e. like the scale depth of 122 m used for explosions in Nevada [39-40] or by the presence of fluid circulation above salt domes that reach nearly to the surface. Fluid circulation could bring bomb-produced radioisotopes like those of xenon to the surface where they might be detected in an on-site inspection. An evader of a CTBT using in a cavity in salt who was determined not to be caught cheating would probably overbury a clandestine decoupled nuclear test. An advantage of constructing a cavity at a depth of at least several hundred meters would be that lithostatic pressure is larger there than at shallow depth, permitting a larger decoupled explosion for a given cavity volume by the criterion of Eqn. (1).

A great deal of experience is now available on stability of cavities formed in salt by solution mining for various industrial purposes such as oil and gas storage and waste disposal [18-19, 45-46, 66]. Solution mining is now the most common form of cavity construction in salt, especially for making very large cavities such as those required for full decoupling of explosions of 1 to 10 kt. It should be appreciated that at the end of the solution mining process that a cavity formed by that method is brine-filled and as such is not suitable for decoupled testing until the brine is removed.

Berest and Minh [66] give criteria for stability of large industrial cavities created in salt. They conclude that large convergence of the walls of cavities occurs when the overburden stress, ρgh, minus the internal cavity pressure (i.e. that produced by either gas under pressure or the vertical stress produced by the brine or other product in the cavity) exceeds 20 MPa. They find that the maximum depth, h, of a stable brine-filled cavity created by solution mining is about 2000 m. In their study of cavity construction in the U.S.S.R., Gaev et al. [46] do not advocate development at depths greater than 1500 m. Berest and Minh also describe several large industrial cavities at depths of 1300 to 2000 m that were operated at low internal pressures that suffered large reductions in volume.

The maximum depth of 2000 m for a brine-filled cavity cited by Berest and Minh is not applicable to the conduct of a decoupled nuclear test since brine in a cavity (or product replacing it like oil or gas under pressure) provides considerable support for the cavity. Using the above criterion of Berest and Minh, the maximum depth of an air-filled cavity at atmospheric pressure is about 900 m for salt. A recent film "Volga, the Soul of Russia" by National Geographic Explorer mentions that 13 of the 15 cavities formed by nuclear explosions near Astrakhan (Figure 3) are no longer usable [for their original purpose, storage of gas condensates]. The depths of the 15 cavities is between 920 and 1100 m [12, 63]. The cavity created in salt by the 1971 explosion at Azgir at a depth of 987 m, however, did not collapse since it was used for a decoupled test in 1976. Presumably that produced by the 1971 explosion at Orenburg at a depth of 1140 m did not collapse [43] although it is not known how soon it was filled with gas condensates, its stated industrial purpose.

From the three examples reported by Berest and Minh [66] and the experience of cavity failure in the FSU and elsewhere, the maximum depth of a stable air-filled cavity in salt ranges from about 900 to 1300 m and depends on the thermal gradient, water content, brine content of the rock salt, percentage of other weaker evaporite minerals such as KCl that are present along with NaCl, and proximity to surrounding brittle rocks [67]. Thus, the range of depths possible for clandestine nuclear testing in salt for yields of a few kilotons or larger is very limited since a minimum depth of about 200 m would be necessary to insure containment. At Astrakhan and Karachaganak the minimum depth is greater since the cap rock above salt extends to depths of about 730 and 330 m [12]. Hence, cavity stability cannot be insured except at quite shallow depths in the crust, depths shallower than those of many salt bodies and depths much shallower than those of many oil and gas wells. For example, a salt deposit at a depth of 5 km cannot be used to create a large cavity.

Sterling was almost, but not fully decoupled; P was a factor of 1.8 = 0.38 / 0.21 times larger than that calculated for full decoupling by the Latter criterion, k = 0.5 in Eqn. (1). The value k =

0.90 appropriate for Sterling indicates, however, that P still did not exceed the vertical stress, k = 1.0. Berest and Minh [66] state that experience with cavities in salt used for high-pressure gas storage indicates that leakage may occur when the internal pressure in the cavity exceeds the vertical stress . In fact, Latter [8] was well aware of this "general rule of thumb" during the initial work on decoupling 35 years ago. While the step in pressure produced by the 1976 explosion at Azgir exceeded the vertical stress by about 1.5 times, it is not known if bomb-produced radioisotopes were detected at the surface or if those products from the 1971 explosion or other nearby explosions at Azgir would have masked such effects. Masking, of course, would not occur for an explosion set off in a cavity produced by conventional or solution mining.

11. Decoupling Scenarios

11.1 COUNTRIES FOR WHOM DECOUPLING IS A POSSIBLE MODE OF CLANDESTINE TESTING

Insuring containment with a high degree of reliability is a necessary condition for conducting decoupled nuclear testing under a CTBT, as it would be for any type of underground nuclear testing. Of the countries that have tested nuclear weapons already, only Russia and the United States, and perhaps China, seem to be possible candidates for conducting decoupled nuclear tests that have a high probability of being contained. Each of those three acquired containment experience, such as insuring that radioactive products do not leak along monitoring cables or along joints and faults, over many underground nuclear explosions and many years [22, 68]. Countries lacking testing and containment experience would take a great risk in attempting to test for the first time in the yield range of a few kilotons or larger and to have high confidence that containment and secrecy would be assured and that the nuclear test would not be identified by outside parties to a CTBT. Most of the countries considered to be likely potential proliferators are small in size relative to the FSU, the U.S. and China, and hence would be easier to monitor from adjacent countries.

Of the present nuclear weapons states only Russia and the U.S. have conducted decoupled nuclear explosions. While having considerable underground testing and containment experience, Britain and France seem unlikely candidates to conduct decoupled explosions in salt unless they would do so in another country. In that case, even granted that they could obtain permission from another country to test on their territory, secrecy would be more likely to be compromised. The U.K. has tested in Nevada for several decades and seems unlikely to do so elsewhere, especially in salt. Relatively small countries like Britain, France and Israel with a high population density seem unlikely candidates for nuclear testing on their own territories.

Davis [69] examined possible sites where either India or Pakistan could test in cavities in salt. India largely consists of old geologic terraines lacking salt deposits. Davis concludes that salt deposits in India appear to be either too thin or too deep to be useful for cavity decoupling. India's experience in nuclear testing is confined to a single explosion. The only place where a massive salt body is accessible in the Indo-Pakistan subcontinent is in the Salt Range Thrust zone of northern Pakistan [69]. While Pakistan is presumed to possess nuclear weapons, it lacks testing and containment experience. It seems highly unlikely that a country that lacks both would attempt a clandestine nuclear test of a few kilotons or larger in large air-filled cavity in salt, which presents additional technical challenges. As discussed in section 11.5, the challenges are much greater and any experience is lacking for conducting and containing a nuclear test of that yield in a large cavity in hard rock.

11.2 TESTING IN CAVITIES PRODUCED BY PREVIOUS NUCLEAR EXPLOSIONS

Tamped nuclear testing in salt that could have produced standing cavities is known to have been conducted only in Russia, Kazakhstan, the Ukraine and the U.S. The single explosion in the Ukraine [12, 63] and the two in the U.S. were small enough that their cavities could not be used for full decoupling of yields larger than 0.2 kt (or 0.4 kt for Sterling conditions, k = 0.9). In

addition the 3.8 kt explosion in the Ukraine was detonated at a depth of 2483 m [63], making it too deep to form a standing, air-filled cavity. As shown in Table 1 most of the larger cavities produced by nuclear explosions of the FSU are now located in Kazakhstan. Cavities formed by past explosions that might be suitable for decoupled testing in Russia itself are limited to fully decoupled yields smaller than 1 kt. Several of those cavities may not be suitable for clandestine nuclear testing either because they have collapsed or undergone considerable deformation, as at Astrakhan, or are located very close to major industrial facilities that could be damaged by such an explosion. Kazakhstan itself lacks testing experience and has signed the Non-Proliferation Treaty. Hence, the monitoring of cavities produced by past nuclear explosions in salt that could be used for fully decoupled nuclear tests larger than 0.5 kt or for somewhat larger partially decoupled explosions is easily manageable under a CTBT given appropriate verification measures in the treaty.

11.3 DECOUPLED TESTING IN MINED CAVITIES IN SALT DOMES

The use of large cavities created in salt domes by solution mining for decoupled testing appears to constitute the greatest challenge to the verification of a CTBT. This evasion scenario seems most applicable to the U.S., Russia and perhaps China, each of which contains domed salt deposits, is a large country, and has considerable testing and containment experience. Most of the salt dome areas of the U.S. and the FSU, however, are characterized by low natural seismicity and efficient propagation of seismic waves, making detection and identification easier. The sizes of chemical explosions used in mining of salt are small to negligible. Monitoring salt domes in areas of natural seismicity and inefficient propagation of seismic waves as in Tadzhikistan, might require special verification measures, such a local seismic array.

In the United States the idea of testing in a large cavities in salt created by solution mining figures prominently in worst-case cheating scenarios from the presentation by Latter [8] in 1959 and the hearings conducted by the Joint Committee on Atomic Energy in 1960 [27] to the 1994 Issue Paper by the Defense Nuclear Agency [19].

Table 4 indicates decoupled nuclear tests of various countries over the last 35 years. While the U.S.S.R. and the U.S. have each conducted a single such test in a cavity created in salt by a previous larger tamped nuclear explosion, no country is known to have conducted a nuclear explosion in a cavity created in salt by either solution or conventional mining. This is indeed both remarkable and odd since that scenario has figured so prominently for decades in arguments in the U.S. that the U.S.S.R. would cheat on a CTBT by that method and in recent claims that potential proliferators like either Iran, Iraq, Libya, Algeria or Pakistan that contain salt deposits could use it for evasive testing. Some have argued that the U.S. could not conduct such an experiment because of environmental opposition and/or its large cost but that some other countries would not face those problems, especially if they wanted to test a weapon badly enough. A different explanation of this lack of experimentation is that this cheating scenario would be found to be very difficult or impossible to carry out in a clandestine manner at yields of a few kilotons or larger if a test of the method, in fact, was conducted.

Very large cavities have been created in salt domes by solution mining [14, 18-19, 45-46, 66]. Most existing cavities, however, are quite non-spherical--typically cylindrical or mushroom shaped--with their longest dimension in the vertical direction. In addition, nearly all are not free standing, i.e. they are filled with brine or stored industrial products [39, 66], either of which must be removed to permit significant decoupled testing. In terms of monitoring a CTBT the issue is not merely what size cavities can be made by solution mining but what can be built, evacuated and used successfully in a clandestine weapons testing program.

While it is possible to construct large cavities in salt by solution mining that are nearly spherical in shape, greater amounts of water, time and expense are need for a given volume than is the case for typical industrial cavities of non-spherical shape. About 10 times the volume of water is need to solution mine a nearly spherical cavity of a given size. The huge volume of water that would be needed to form a nearly spherical cavity suitable for the full decoupling of say a 10-kt explosion is not available in and near many areas of thick salt deposits. For example, the Azgir region is quite

arid, as is much of the Pre-Caspian depression [5]. Large volumes of water in the depression are available only along the north coast of the Caspian Sea and the Volga and Ural rivers. Most other rivers end in ephemeral lakes.

Disposal of huge volumes of brine from a very large cavity would not be a trivial endeavor in many areas. One method would be to inject the brine into disposal wells in an oil or gas field. This solution, of course, requires such the presence of a field. For example, no such field exists in or near Azgir. While relatively few disposal wells have had seismicity associated with them, enough have that an evader contemplating removing brine from a large cavity would have to take into account that small to moderate-size earthquakes may accompany injection, especially if it is done rapidly. While it is possible that brine could be disposed clandestinely into a large river or lake in forming a cavity suitable for a decoupled test in the sub-kiloton range, disposal of the much greater volumes of brine from a cavity suitable for full decoupling of say a 10-kt explosion, even if done over a period of a few years, would likely be detectable in the waters of rivers and lakes.

Very few large cavities created by solution mining, in fact, have been evacuated and depressurized. Large pumps would be needed to remove brine from a very large cavity and their presence detected by satellite and other intelligence. The flow of water into some large cavities may be fast enough that it may not be possible to remove water and brine from them in an expeditious amount of time. While some cavities undoubtedly can be evacuated, a country investing time and resources in making a large, nearly spherical cavity in salt by solution mining would have to face the possibility that it would not know prior to construction that it, in fact, could be evacuated.

Little is known about the rheological properties of the walls of cavities formed by solution mining and about how far fluids and defects have penetrated into the surround salt. In addition, a long debate has taken place in the engineering, geological and petroleum literature about the rheology of salt *in situ* in salt domes and bedded salt. Jenyon [67] states on page 170 "Frequently, in the interior of a salt diapir, bands of other lithologies--anhydrite, dolomite, clays and bitterns--some of which are more soluble and more easily deformable than halite [NaCl], exit together with brine-filled cavities and sometimes joints. Such irregularities and discontinuities within the salt must be detected and their potential effects on storage assessed carefully." The flowage of brine from the surrounding salt body into mined openings at the W.I.P.P. site in southeastern New Mexico has constituted a major problem in terms of certifying that site for high-level radioactive waste disposal [70]. Engineering studies of small laboratory samples of rock salt often yield different rheological properties than are inferred by mining geologists based on bulk properties on a scale of 10s to 100s of meters. My sense is that not enough attention has been given to rheological properties of salt on those larger scales in code calculations in the U.S.

The maximum yield of a decoupled explosion that can be conducted in a cavity created in salt by solution or conventional mining is mainly governed by the identification capabilities of seismic networks and less by the maximum sizes of cavities that can be created. For example, an identification capability at the m_b 3.0 level for the FSU, China and the U.S., which is now being considered at the CTBT negotiations in Geneva, would permit fully decoupled explosions of a few kilotons to be not only detected but also identified in areas of efficient seismic wave propagation. A capability at the m_b 3.4 level would permit fully decoupled explosions of 10 kt to be identified. Thus, claims that cavities can be created by solution mining for the full decoupling of up to 50 kt [18-19] do not take into account seismic and other identification capabilities that seem likely to come into existence over the next few years. It is reasonable that satellite imagery and air reconnaissance of areas of thick salt deposits of appropriate countries would be stepped up or implemented under a CTBT. They could help to identify special drilling rigs, pumping equipment, emplacement of nuclear devices, large numbers of personnel and monitoring equipment even if attempts were made to mask their presence by an industrial operation. There is no question, for example, that the presence of such facilities at Azgir, a region of no industrialization, would be easily detected by such surveillance.

The above identification capabilities represent a high level of confidence in detecting a violation of a CTBT. A country contemplating a decoupled nuclear test in a cavity created in salt by solution

mining and wanting to have a high probability of not being caught would have to consider yields much smaller than those given above. In addition that country would have to weigh conservatively the fact that a nuclear test of significant yield has not been conducted in a cavity created by solution mining, uncertainties in the rheological properties of salt on a scale of 10s to 100s of meters, the chance that after it is evacuated of brine that a cavity may collapse or suffer enough deformation that it could not be used for nuclear testing, and that the disposal of brine may be detected.

11.4 CAVITIES IN BEDDED SALT

Cavity construction in areas of bedded salt is more limited since salt is typically interbedded with other rocks such as dolomite, anhydrite and limestone on a scale of 10s to 100s of meters. Jenyon [67] states that care must be taken not to put strong rocks above salt beds under tensional stress by making cavities too close to the top of the salt. To satisfy this requirement the diameter of a cavity should no more than half the thickness of a salt unit. Thus, at the depth of the Salmon cavity, 828 m, a salt layer would need to be at least 112 m thick for full decoupling of 1 kt and 224 m for 8 kt. Sterling conditions, $k = 0.9$ in Eqn. (1), would lead to those yields being multiplied by 1.8 for the same thicknesses and depth.

The FSU conducted a single small nuclear explosion in salt [12] in the large area of bedded salt to the northwest of Lake Baikal (Figure 2). Its yield, 4.9 kt [63], slightly smaller than that of Salmon, was small enough that its cavity could not be used for significant decoupled testing. Seismic activity along the Baikal rift does not extend as far to the north and northwest as the boundaries of those salt deposits. Earthquake activity within the salt deposits themselves appears to be very low. The area is also one of low population density and few towns and roads.

Zharkov [71] describes numerous boreholes and stratigraphic logs of boreholes drilled into that area of bedded salt. While the total series of Cambrian salt deposits in that region reaches thicknesses of up to 2000 m, the maximum thicknesses of individual salt units, for which Zharkov gives detailed isopach maps and stratigraphic cross sections (pages 20-45), rarely reach 100 to 150 m. Many of the thicker units are located at depths in excess of 900 to 1300 m, the maximum depth of a stable air-filled cavity in salt, as described in section 10. Thus, the maximum fully decoupled yield possible in those places where the thicker salt beds are found at shallower depths is close to 1 kt (about 2 kt for Sterling conditions). In a few places fully decoupled yields up to a few kilotons may be possible. As pointed out by Zharkov, however, the geology and salt content of those deposits varies spatially. That inhomogeneity makes bedded salt more difficult to use for cavity construction compared to that for many salt domes. A similar situation exists for the Silurian salt deposits that extend from northern New York to Michigan. Many of the individual salt units are relatively thin compared to the requirements for significant decoupled nuclear testing. Most of the thicker units are at depths too great for the construction of stable air-filled cavities.

11.5 CAVITIES IN HARD AND SOFT ROCK

11.5.1 *Millyard Decoupled Explosion in Dry Tuff*

Table 4 indicates that no country is known to have tested a decoupled nuclear explosion in hard rock. The tiny Millyard nuclear explosion, a decoupled event, was conducted on October 9, 1985 in Nevada in softer rock--dry tuff--in a hemispherical cavity with a radius of 11 m at a depth of 375 m [16, 72-73]. In 1986 Garbin [72] calculated a maximum DF of 60 to 70 for Millyard by scaling it to the Diamond Beech explosion, which was detonated on the same day as Millyard, at the same depth and recorded by the same equipment. He describes Diamond Beech, however, as being two orders of magnitude larger than Millyard. The great difference in size of the two events and that they must have been offset horizontally from one another make the estimate of DF only an approximate one. Since Millyard was so small and was decoupled, seismic waves could only have been recorded from a small range of takeoff angles and probably not for seismic rays leaving the source near the intersection of the hemisphere and the floor of the cavity. In 1993 Garbin [73] states that Millyard was completely decoupled and that ground motion was reduced by at least a factor of 70. He goes on to give DF = 70 at 3 Hz. and 10 at 30 Hz.

Stevens et al. [16] calculated a maximum fully decoupled yield of 0.021 kt (21 tons) for the Millyard cavity and a maximum decoupling factor of 44. Assuming Millyard was fully decoupled and its yield was about 0.021 kt, scaling its radius to 1 kt gives 40 m. Since the cavity was hemispherical in shape, however, it may be more appropriate to scale its volume to 1 kt, giving a scaled radius of 32 m.

Garbin [73] states that there have been a number of nuclear tests in Nevada inside hemispherical cavities, including Millyard and Misty Echo, the latter of which he states was fired in the same size cavity as Millyard but of much larger yield. He concludes that Misty Echo was not decoupled but instead may have shown small enhanced amplitudes with respect to the Mineral Quarry explosion, which was detonated 1 km from Misty Echo but at nearly the same depth. The latter two events were detonated in saturated tuff. Stevens et al. [16] also describe two explosions in 11 m hemispherical cavities in saturated tuff with yields of 0.5 and 2.0 kt that were overdriven by factors of 24 and 95. One of these may have been Misty Echo.

In summary, the evidence available indicates that only one very tiny explosion nuclear explosion, Millyard, was conducted in tuff in Nevada with a sizable but uncertain decoupling factor. A cavity suitable for full decoupling of 1 kt in the same rock type would have to be about 50 times larger in volume, a significant engineer achievement compared to the mining of the Millyard cavity.

11.5.2 *Uncertainties in Scaled Cavity Radius for Full Decoupling in Hard Rock*
A major issue that has received little debate is what is the maximum size cavity that could be constructed and used for clandestine, fully-decoupled testing of a given yield in hard rock? Patterson [32-33] estimated scaled cavity radii for granite and salt for nearly full decoupling at depths of about 1000 m as 20 and 30 m. The 20 m value for granite, which continues to be widely used and quoted [19, 41], is based, however, on free-field measurements for early U.S. explosions in granite that were thought then to be in the elastic regime but most of which are now widely regarded as being in the inelastic regime. The Defense Nuclear Agency's issue paper on the feasibility of decoupled testing [19] cites a scaled radius for granite of 25 m but then goes on to use the value of 20 m from the 1988 OTA Report [14] stating it is "based on more refined calculations that include the effects of material strength." Since I was a member of the various OTA panels that were involved in assessing this subject, that statement is not correct. The figure of 20 m in the OTA Report was taken entirely from the 1966 work of Patterson [32-33], which was also used by Terhune et al. [41]. While 20 m was attributed by those authors to a weakened granite, it is not clear if that number is, in fact, appropriate to granite or other hard rocks *in situ* on a scale of a very large cavity, one of radius of 30 to 100 m.

Heuzé, Heuzé et al. [74-76] and many engineering reports on the construction of underground openings emphasize that hard rock masses are seldom monolithic but are penetrated by numerous joints, faults and other discontinuities. Heuzé et al. [76] state that traditional continuum codes are not sufficient for simulating multiple dynamic block motion processes for underground nuclear explosions in such media. Since no country is known to have conducted a decoupled nuclear explosion in hard rock, the scaled radius for full decoupling at a depth of say 1000 m should be taken to be quite uncertain. On a scale of 20 to 200 m, hard rock *in situ* may well have a scaled cavity radius for full decoupling more like that of salt. A scaled radius of 25 to 30 m seems more appropriate for those conditions.

11.5.3 *Existing Underground Openings in Hard Rock*
The volumes and diameters of the largest existing underground cavities in hard rock are much smaller than those formed by solution mining in salt [18-19]. Leith and Glover [18] list 10 unsupported cavities mined in hard rock with volumes greater than 280,000 m^3. The depths of at least 5 of those are too shallow for containment of even a 1 kt explosion. The smallest dimension (width) of the deepest, 351m, is only 28 m. The line of argument advanced by Leith and Glover [18] and Knowles et al. [19] that such cavities can, in fact, be constructed at depth and used for decoupled testing at yields well in excess of 1 kt depends on two untested assumptions for hard

rock: 1) volume, not the smaller one or two dimensions of an underground opening, is the critical dimensional factor controlling DF and 2) the scaled radius is 20 m for full decoupling. Use of scaled radii of 25 to 30 m for hard rock, which I believe is more appropriate, leads to a reduction in the maximum fully decoupled yields calculated by Leith and Glover [18] and Knowles et al. [19] for cavities in hard rock by a factor of about 2.0 to 3.4. Code calculations for very non-spherical cavities in hard rock are likely to be even more uncertain than they are for salt given the presence of joints and large differences in principal stresses. Overdriven decoupled testing in hard rock is more likely to result in leakage from a cavity than one in salt. The latter two factors are examined further in section 11.6.

Leith and Glover [18] describe the underground room created in Norway for an ice hockey arena for the 1994 Winter Olympics. The project was undertaken to display Norwegian capabilities in rock mechanics and underground excavation. While the room has an unsupported span of 61 m, its stability as a large underground arena should not be taken as indicative of the use of such a structure for underground nuclear testing. First, the depth from the surface to the top the room, 25 to 50 m, was so shallow that containment would not be possible except at yields far below 1 kt. In addition, the shock wave and the step in pressure from a decoupled nuclear explosion would drive the cavity farther from stability by decreasing the compressive hoop stresses in the rock surrounding the cavity. Unlike salt, hard rocks *in situ* in the earth, like those at the Norwegian site, are typified by large differences in principal stress. The difference between the maximum and minimum principal stresses typically increases with depth in the first few kilometers of the earth, making construction and stability more difficult at greater depth. Rockbursts typically become a greater problem in mines as the depth of underground openings becomes greater.

If the scaled radius for granite and other hard rocks is taken to be 25 to 30 m, the construction of nearly spherical cavities at depths suitable for the full decoupling of nuclear explosions larger than about 1 kt is as yet unproved as is the construction of such cavities at depths greater than 500 m. A country intent on successful evasion of a CTBT at the few kiloton level or larger using a large, nearly spherical cavity in hard rock would have to contend with much greater uncertainties than those for a large cavity in salt that arise from the following: 1) the greater difficulty of insuring containment given the presence of joints and large differences in principal stress, the fact that only small nearly-spherical openings have been constructed at depths greater than 500 m, and the lack of any known decoupled nuclear test in a large cavity in hard rock.

J. E. Carothers, a Livermore scientist who was formerly responsible for nuclear testing in Nevada and the former head of the Containment Evaluation Panel that must approve each U.S. underground nuclear test, was asked to speak on the feasibility of decoupled nuclear testing in hard rock at a symposium on nuclear testing and non-proliferation at Princeton in 1992 [68]. He stated that the creation of a cavity in hard rock to fully decouple 20 kt would be an unprecedented engineering accomplishment, would be very expensive, that joints would present major containment problems, the Containment Evaluation Panel would likely not approve such a nuclear test and that he would not go into such a cavity even with a hardhat.

11.6 PARTIALLY DECOUPLED EXPLOSIONS AND NON-SPHERICAL CAVITIES

A major issue going back to 1959 is what is the decoupling factor for a partially decoupled nuclear explosion? Overdriven explosions, i.e. ones in cavities too small for full decoupling of a given yield, necessarily involve non-elastic stresses in the material surrounding the cavity. That problem is not susceptible to the simple elastic solutions of a pressure pulse on the walls of a cavity in a perfectly elastic material.

The data in Figure 6, especially that for the Soviet partially decoupled explosion at Azgir in 1976, indicate that the decoupling factor drops rapidly for cavities overdriven with respect to Sterling conditions, i.e. for long-term cavity pressures greater than about 1.5 times the lithostatic (overburden) stress or about 3 times the Latter criterion. Code calculations by Patterson [32-33] and Stevens et al. [16] fall well above the data for the Azgir and Cowboy overdriven explosions of $Y/Y_L > 2.0$ in Figure 6. The code calculations of Glen and Goldstein [42] only come close to

fitting the data when the yield of the 1976 explosion is taken to be 11.5 kt, their own DF = 27 as obtained from stations at close distances is used, and the smaller DF obtained at larger distances (Table 2) is ignored. Regardless of the yield of the 1976 event, the recent code calculations by Glen and Goldstein [42] and Stevens et al. [16] do not agree for overdriven spherical cavities in salt. Thus, while the best data on partial decoupling exist for chemical and nuclear explosions in nearly spherical cavities in salt, code calculations for that case, which have been made for about 30 years, are still not consistent with one another and usually predict values of DF that are too large.

Before Glen and Goldstein [42] published their 1994 paper, a year earlier Goldstein and Glen [62] reviewed much of the same data but taking the yield for the 1976 event to be 8 kt, not 11.5 kt as in their 1994 paper. The title of their 1993 paper was "Modelling of tamped and decoupled explosions in salt: (Simulation is easy. Prediction is Difficult!)" Any remarks about the ease of simulation and the difficulties of prediction are absent from their 1994 work and from the Issue Paper of the Defense Nuclear Agency [19]. That 1993 subtitle needs to be remembered in evaluating the accuracy of code calculations, even recent ones. A country wishing to test clandestinely by overdriving a cavity in salt, even one with considerable experience in code simulations, would have to take those uncertainties into account and test in a conservative manner if it wished to avoid being caught cheating.

In the last several years scientists at Livermore [77] and S-Cubed [15, 17] have also performed code calculations of decoupling factors for non-spherical cavities in salt. The S-Cubed simulations examined the decoupling performance of ellipsoidal cavities with an aspect ratio (ratio of longest to shortest dimension) of 4:1 and found DF to be similar to that of a spherical cavity of equal volume. In those calculations the walls of non-spherical cavities in the direction of the shortest dimension are subjected to non-elastic stresses, as in the case of overdriven spherical cavities. Since similar calculations fit the observed data in Figure 6 so poorly for nearly spherical cavities in salt for overdriven explosions, the results of code calculations for ellipsoidal and other non-spherical cavities in salt should be viewed with considerable skepticism.

Leith and Glover [18] and Knowles et al. [19] calculate the yields of decoupled explosions that could be detonated in overdriven cavities in both salt and hard rock and for non-spherical cavities with aspect ratios of 4:1 as in the S-Cubed study [16]. They assume that DF is largely controlled by the volume. In an abridged version of the Knowles et al. [19] paper the authors state that decoupled tests appear feasible up to at least 10 kt and perhaps to 50 kt *for both salt and hard rock.*. They speculate that if aspect ratios of 10:1 or more are acceptable, the construction of cavities to mask 50 kt become easier. The application of results on overdriven cavities and very non-spherical cavities in salt to hard rock seems especially tenuous. Decoupled explosions in salt of a yield greater than a few kilotons, regardless of the shape of the cavity, are likely to be identified as such as discussed in section 11.3 for identification thresholds of about m_b 3.0.

One set of data on chemical explosions fired in spherical and non-spherical cavities in limestone in Kirgizia by the U.S.S.R. in 1960 bears upon the decoupling factor for non-spherical cavities. and overdriven cavities. Information on those decoupled and partially decoupled explosions has only recently become available outside the FSU. In some of those experiments explosives were suspended in the centers of chambers while in others they were detonated off-center near the cavity wall [13]. Those detonated near the cavity walls produced larger seismic waves than those detonated near the center. The results released thus far indicate that a portion of the walls of a cavity being driven into the non-linear regime results in a smaller decoupling factor compared to an explosion in the center of the cavity even when the volume is the same in the two cases. This result differs from that obtained by code calculations in the U.S. for nuclear explosions in non-spherical cavities and for overdriven, partially decoupled nuclear explosions. The Kirghiz experiments also indicate a maximum low-frequency decoupling factor of the order of 40 to 50 for limestone.

11.7 NUCLEAR TESTING IN CAVES, MINES AND OTHER EXOTIC SCENARIOS

Leith and Glover [18] describe a number of other possible decoupling scenarios. They state that very large underground spaces have been built as "room and pillar" structures in conjunction with the mining of gold, coal and copper. They mention, however, that the decoupling effectiveness of such structures is unknown. Nevertheless, they go on to state "Room and pillar mines may be ideal locations for decoupling nuclear explosions if the volume is great enough. The pillar would act as 'energy dumps' and, thereby, help to enhance decoupling." There are several objections to this decoupling concept. First, no decoupled nuclear test is known to have been conducted in this manner. Second, these underground openings are very non-spherical in shape. Leith and Glover make the assumption, which I criticize in section 11.6, that it is the volume that controls the decoupling factor and that DF can be predicted with confidence. Existing mines have many shafts, drill holes and other openings all of which would be difficult to locate and seal so as to prevent leakage of bomb-produced radio-nuclides, especially if the mine openings in the shortest direction are overdriven by a nuclear explosion. Pillars are likely to collapse, making observations of the explosion difficult and collapse possible. Again, containment, not volume alone, is the key to the success or failure of this evasion scenario.

A large section of a mine in western New York State, the largest active salt mine in the United States, collapsed and flooded in 1994 [79]. A visible surface depression was also produced. Collapse followed very active mining in response to the need for vast quantities of road salt during the severe winter of 1994 in the northeastern United States. Failure resulted from underground rooms being mined in salt with a smaller percentage of support pillars than normal. Removal or damage to pillars by a nuclear explosion, whether they are in salt or some other material, risks mine failure, and possible loss of containment.

Leith and Glover show the large area of a room and pillar coal mine in South Africa and pose the question "What is the decoupling effectiveness of such a structure?" Coal, a weak sedimentary material, would be an unlikely medium for clandestine nuclear testing given its low strength, anisotropic layered properties and volatile content. The shortest dimension of underground openings in coal and in gold mines in layered rock sequences, i.e. that perpendicular to bedding, is typically very small--of the order of meters. Mine openings at great depth in South African gold mines are kept open near the working face with large jacks, which are then removed, permitting collapse, once that working face moves forward. Although the volume of such openings may be large, the aspect ratio of such structures is very large. A nuclear explosion of significant yield detonated in such a structure would undoubtedly generate large seismic waves in directions nearly normal to the shortest dimension, which is typically only meters.

A feature of most underground mines is that they contain volumes of mineralized rock whose strength is typically lower than that of most hard rocks. Knowles et al. [19] admit that the settings of economically valuable minerals may not be the geologies conducive to construction of large cavities or containment of radioactive gases. They suggest, however, that the cost to create a cavity in a mining district can be offset partially by the value of the ore extracted. Problems of containment and cavity stability, however, would seem to offset that possible savings.

Leith and Glover [18] also consider nuclear explosions conducted in the rubble zone or chimney of a previous explosion. While nuclear explosions fired in rubble zones of previous nuclear explosions or in fault zones at test sites in Nevada and eastern Kazakhstan are known to have generated smaller than normal seismic waves, this effect is mainly a problem for accurate yield estimation. The reduction in m_b was not large, especially when compared to a DF of 70 for full decoupling in a cavity in salt, and is similar to detonating an explosion in a lower-coupling material. Again, containment would be a problem, as Leith and Glover acknowledge may be the case.

Leith and Glover give a table of the dimensions of large natural caverns. While some caverns have large spans and volumes, they state that "the locations, geometry and extent of large caves are generally well known, and the containment capabilities of most large caverns are probably poor due to open connections with the atmosphere. Most dry caves are shallow (<100 meters), and it is

probably unfeasible to drain the deeper caves that are water-filled." Evernden [28] reached similar conclusions in 1976. In addition most natural caves are partly occupied by columnar structures that divide the total underground space.

In these and several other of the alternative decoupling methods discussed by Leith and Glover [18] containment and other problems are so serious that they should be regarded as exotic, bizarre cheating scenarios. Killian's [9] injunction to make clear the difference between probability and possibility seems most appropriate for these scenarios.

In considering decoupled nuclear tests in cavities in a variety of rock types with aspect ratios of 4:1 and perhaps 10:1, Knowles et al. [19] state that the residual cavity pressure is a matter of potential concern because of containment requirements and possibilities of measurable seepage through cracks and fissures. They give an example of a 10 kt detonation in a cavity with a volume of 10^5 m^3, stating the residual cavity pressure would be about 800 bars (80 MPa). They go on to state that such pressures would probably cause seeps of radioactive gases that might be detected at the surface, especially in fractured rock geologies, and that such leakage is more likely in the hard rock geologies typical of most mining operations. That pressure is about 3 to 6 times the lithostatic stress at depths of 500 to 1000 m. Even outside of mining districts hard rocks *in situ* have enough joints on a spacing of meters to tens of meters that pressures considerably smaller than 800 bars would likely hydrofracture those joints and serve as pathways for escape of radioactive gases. In many areas of hard rock the least compressive stress, which is of greatest importance to hydrofracturing, is considerably smaller than the overburden stress.

Knowles et al. [19] seek to escape the problem of high pressure and leakage by proposing to make a still larger connected chamber into which the gas pressure would be directed and hence reduced. They propose to do that for the above 10 kt example by extending a cylindrical tunnel 230 m long of 10:1 aspect ratio to a length of 2 to 3 km so as to reduce the residual pressure to about 80 bars, thus reducing the likelihood of radioactive leakage. Additional construction of this type would seem to invite more problems than it would solve in that additional joints would likely be encountered and the additional mining required would make detection of such a facility easier to identify. This scenario seems to pile one untested hypothesis upon another.

12. Chemical Explosions in and near Salt Deposits--the Azgir Region

A special study was made of small seismic events reported by the ISC, Norsar and Lasa in the 5^o by 5^o box outlined in Figure 3 that includes Azgir and Astrakhan for the 23-year period 1969 through 1991. The special study area represents about 45% of the Pre-Caspian salt dome province. From 1966 to 1984 the region was the site of 26 nuclear explosions of $m_b > 4.5$ near either Azgir, Astrakhan or Lake Aralsor, all of which are well located by either standard reporting services or by using master-event techniques. Events of $m_b > 4.5$, equivalent via Eqn. (2) to a tamped nuclear explosion of 1 kt, from that region have been regularly reported by ISC since 1966. The Norsar (NAO) and/or Lasa (LAO) arrays (and occasionally ISC) located 133 small (m_b < 4.5) events in the region but with location accuracies that are poorer than for the above large explosions.

Station corrections for m_b for the Azgir area used in section 7.2 were applied to other seismic events from the above study area. Those for NAO, -0.48; Hagfors, -0.50; LAO, -0.52 were applied in deriving revised m_b's for the small events. The revised magnitudes of those small seismic events were all about 0.5 m_b units less than the original determinations, indicating that they are, in fact, systematically smaller than their uncorrected m_b's would suggest. It should be recognized that the magnitude used is a true teleseismic m_b and not a value based on near or regional recordings such as those of Lg.

The large explosions and nearly all of the small events exhibit strong clustering during daylight hours (Figure 7), indicating that few, if any, are earthquakes. Testing practice since 1971 for the above large explosions and for nearly all Soviet PNEs has been to detonate them to within a few

seconds or less of a given hour. The small events, most of which are interpreted to be chemical explosions, however, are distributed randomly in time during the hour. That chemical explosions were usually not detonated exactly on an exact hour seems somewhat surprising. It is probably indicative that the conduct of a nuclear explosion, unlike standard chemical explosions in the sub-kiloton range, requires great coordination among large groups of people, necessitating planning for the exact time of the nuclear event well ahead of time. It can be seen in Figure 7 that the detonation of nuclear events has usually been confined to morning hours and to a narrower time frame during the day than chemical explosions.

All of the origin times and, with one exception, the locations computed using data from the Norsar array alone for large explosions at Azgir are within 12 sec and 150 km of those computed by the ISC. Seven of the 133 small events fall within 12 s of an exact hour during daylight. Of those 7, one is the partially decoupled event of 1976 and 4 are known to be very small nuclear explosions detonated in the water-filled cavity produced by the Azgir nuclear event of 1968 (Table 3). One of those events occurred outside the time of normally nuclear testing.

Cumulative numbers of the remaining 128 small events from 1969 to 1991 in both the entire study area and within 150 km of Azgir are shown in Figure 8. The slope, **b**, of the log frequency-m_b relation is very large, about 2.7, for $3.6 \leq m_b \leq 4.0$ and 1.1 from m_b 3.1 to 3.6. In a study of blasting activity in the U.S., Richards et al. [78] report **b** ~3 for chemical yields from 100 to 1000 tons and **b** ~1 from 1 to 100 tons, nearly identical to the slopes found in Figure 8 for similar yield ranges. The fact that the data in Figure 8 fall below the **b** = 1.14 line for $m_b < 3.1$ is reasonably attributed to lack of completeness at smaller magnitudes. That and the similarities of the data in Figure 8 to U.S. blasting frequencies indicates that the catalogue is complete or very nearly so for $m_b > 3.1$. The words very nearly so are used since most of the small events were reported by only one to three arrays. Lasa was operating for only a few of the 23 years examined. Norsar experiences a small percentage of down time; it was not operating at the time of two of the smallest nuclear explosions in Table 3, those of m_b 2.77 and 3.07. Nevertheless, $m_b > 3.1$ probably represents completeness at better than the 95% level. It seems reasonable to estimate the number of events of $m_b \geq 2.5$ by extrapolating from the number in Figure 8 at $m_b = 3.2$ using a **b** value of 1.14.

Of the 73 remaining small events located within 150 km of Azgir, the largest in 23 years was a single event of m_b 4.0. Chemical explosions of $m_b > 3.5$ and those of $m_b > 3.0$ have occurred about 0.7 and 2.6 times per year. m_b's of 3.0 and 3.5 correspond to yields of about 3 and 13 kt for nuclear explosions with DF = 70. Thus, the number of chemical explosions per year in that area that must be discriminated as such from small decoupled nuclear events is small even at m_b 3.0. A major uncertainty pointed out by the OTA Report [14] is the number of chemical explosions that must be contended with per year equal in m_b to that of decoupled explosions of a given yield. There is a pressing need to bring together data from arrays in Europe and from stations in Eastern Europe and the FSU to provide more accurate locations of small seismic in this and other areas of thick salt deposits of the western third of the FSU and to avoid problems of down time at single sensitive arrays.

13. Conclusions and Recommendations

Now that a CTBT is under negotiation many issues involving verification that have largely been dormant for many years are surfacing. Several aspects of decoupled nuclear testing are among the prime issues. For a country to believe that it can cheat on a CTBT with high confidence by testing in a decoupled mode at the few kiloton level or above, it must be prepared to pass a series of verification challenges: clandestine construction and evacuation of a large cavity at depth, insure containment, and not be identified by seismic networks, satellite imagery or other verification measures. I argue that countries that lack underground nuclear testing and confinement experience

are unlikely to attempt a decoupled test of significant yield; they are unlikely to be able to pass all of the above verification challenges.

Large cavities created by past nuclear explosions in salt are confined to a few areas of Russia and Kazakhstan and could be monitored relatively easily under a CTBT. The U.S. and the Former Soviet Union have each tested only a single decoupled nuclear explosion in a large cavity in salt, in each case in the cavity created by a previous larger nuclear explosion. The statement in the 1994 Issue Paper by the U.S. Defense Nuclear Agency [19] that the decoupling program of the U.S.S.R. appears to have been much larger than that of the U.S. is not correct. The Soviet Union did, however, conduct a much larger decoupled explosion than the U.S., which provides considerable constraint upon the feasibility of decoupled testing and its identification in the yield range from 1 to 10 kt.

Monitoring salt dome areas of the nuclear powers should be a high priority so as to deal with possible decoupled testing in cavities constructed by solution mining. A country wishing to test clandestinely in a large cavity in hard rock, however, must contend with greater uncertainties in rock properties (such as the presence of joints and other discontinuities) as they affect cavity stability and containment, with differences in principal stresses that generally increase with depth, and with a scaled radius for full decoupling that is probably considerably larger than the 20 m estimated about 30 years ago. Resolving the feasibility of decoupled testing at the few kiloton level for hard rock is critical since hard rock is present in many more areas than salt domes. Since there is no evidence that any country has constructed a large cavity either by solution mining in salt or in hard rock and used it for a decoupled nuclear test, a potential violator of a CTBT deciding to use that cheating scenario would have to do so in a very conservative manner if it wished to have a high probability of not been caught cheating.

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TABLE 1. INVENTORY OF LARGE CAVITIES PRODUCED BY PAST NUCLEAR EXPLOSIONS IN OR NEAR THICK SALT DEPOSITS OF F.S.U. THAT MAY REMAIN STANDING THAT MIGHT BE USED TO CONDUCT FULLY DECOUPLED NUCLEAR TESTS OF YIELD, $Y_{FD} \geq 0.5$ KT.

REGION	Y_{FD} (kt)				
	0.5 - 0.9	1.0 - 1.9	2.0 - 2.9	3.0 - 3.9	4.0 - 4.2
Pre-Caspian Depression					
Azgir		2	4	1*	1
Astrakhan	5				
Karachaganak	5				
Lake Aralsor			1*		
Other	2		1*		
Bedded salt to NW of Lake Baikal	1				
Central Asia - Bukhara			1		
Totals	13	2	7	1*	1

* Reported by Russian workers as detonated in clay.

TABLE 2. MAGNITUDES AND DECOUPLING FACTORS FOR AZGIR EXPLOSION OF 1976.

Station	Distance	(a^{71}/a^{76})	$\log(a^{71}/a^{76})$	m_b
KRV	785 km	670 / 8	1.923	4.14
BRV	1590	786 / 6	2.117	3.95
GAR	2205	470 / 5	1.973	4.09
TLG	2280	620 / 7	1.947	4.12
ELT	2690	650 / 5	2.114	3.95
BOD	4310	650 / 8.5	1.884	4.18
NAO	2760	---	---	3.98
Averages			1.993	4.06
± SEM			± 0.041	±0.04

$m_b = A + B\log Y - \log(DF) - \log(a/T)$

$DF = (a^{71}/a^{76}) / (Y^{71}/Y^{76})^B$

TABLE 3. NUCLEAR EXPLOSIONS IN CAVITIES IN SALT AT AZGIR

Date	Hr.	Min.	$m_b \pm$ SEM	n (m_b)	Yield (kt)
25 April 1975	05	00	4.45 ± .13	7	1.1
*29 March 1976	07	00	4.06 ± .04	7	8**
14 October 1977	07	00	3.42	1	0.06
30 October 1977	07	00	2.77	1	0.01
12 September 1978	05	00	3.02	1	0.02
30 November 1978	08	00	3.07	1	0.02
10 January 1979	08	00	4.36 ± .14	2	0.8

* In air-filled cavity created by 64 kt explosion of 1971; all other events in water-filled cavity created by 25 kt explosion of 1968.

** Yield of 1976 event from Adushkin et al. (10).

TABLE 4. DECOUPLED EXPLOSIVE TESTING

CHEMICAL EXPLOSIVES

1. U.S.A. -- Cowboy explosions in salt -- up to 2000 pounds of explosive
2. U.K. -- Orpheus -- in limestone and granite -- 8 to 64 pounds of explosive
3. U.S.S.R. -- in Kirgizia

NUCLEAR EXPLOSIONS IN SALT

A. IN AIR-FILLED CAVITIES FORMED BY LARGER NUCLEAR EXPLOSIONS
   1. U.S.A. -- STERLING, 1966 -- 0.38 kt -- in cavity of 1964 SALMON explosion
   2. U.S.S.R. -- 1976 -- in cavity of 1971 Azgir, W. Kazakhstan, explosion

B. IN CAVITIES FORMED BY EITHER SOLUTION OR CONVENTIONAL MINING
   1. <u>None Known</u>

NUCLEAR EXPLOSIONS IN CAVITIES IN HARD ROCK

A. None Known

NUCLEAR EXPLOSIONS IN CAVITIES IN SOFT ROCK

A. U.S.A. -- 3 explosions in hemispherical cavities of 11 meter radius in tuff at Nevada Test Site
   1. Highly overdriven events of 0.5 and 2.0 kt;
   2. MILLYARD, about .02 kt. -- decoupled but amount uncertain

B. U.S.S.R. -- None Known

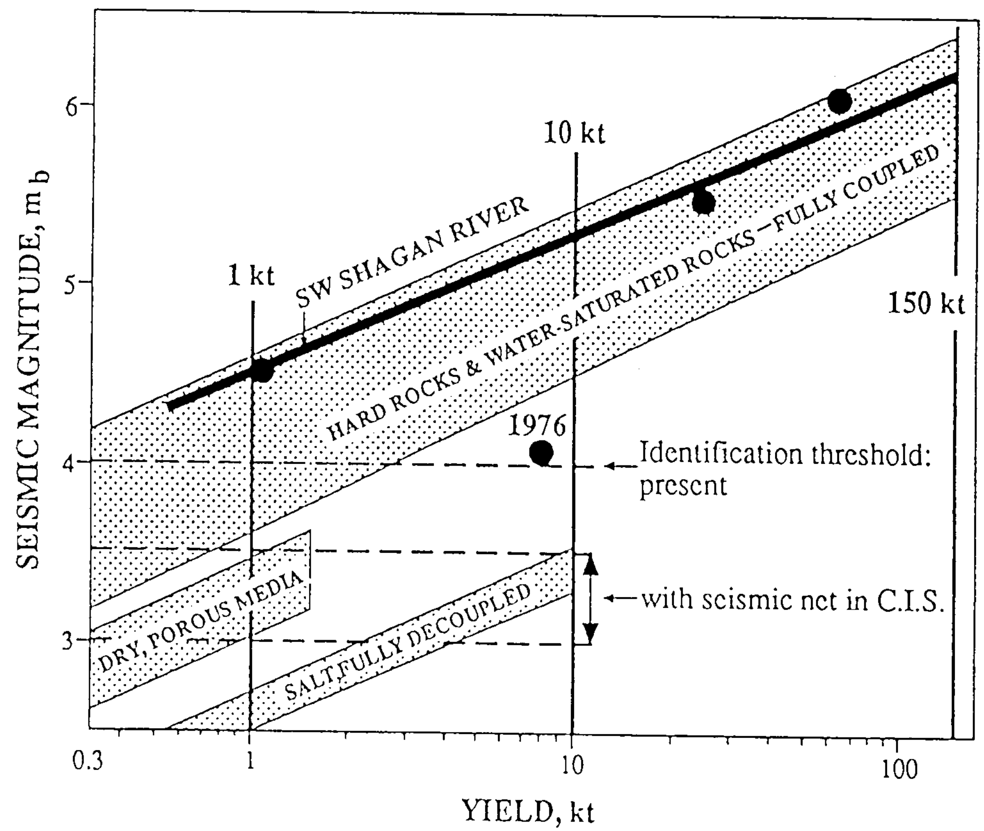

Figure.1. Seismic magnitude as a function of yield for underground nuclear explosions conducted under various testing conditions (hatched areas) in Commonwealth of Independent States (C.I.S.). SW Shagan River denotes regression line for fully-coupled nuclear explosions in southwestern part of that testing area in eastern Kazakhstan from Sykes[2]. Three upper dots denote data points for fully-coupled explosions in salt at Azgir; dot labelled 1976 denotes partially decoupled explosion at Azgir of March 1976; 150 kt denotes yield limitation of Threshold Test Ban Treaty. 1988 identification threshold using seismic stations solely external to C.I.S. and range of thresholds with seismic networks in C.I.S. from Office of Technology Assessment [14].

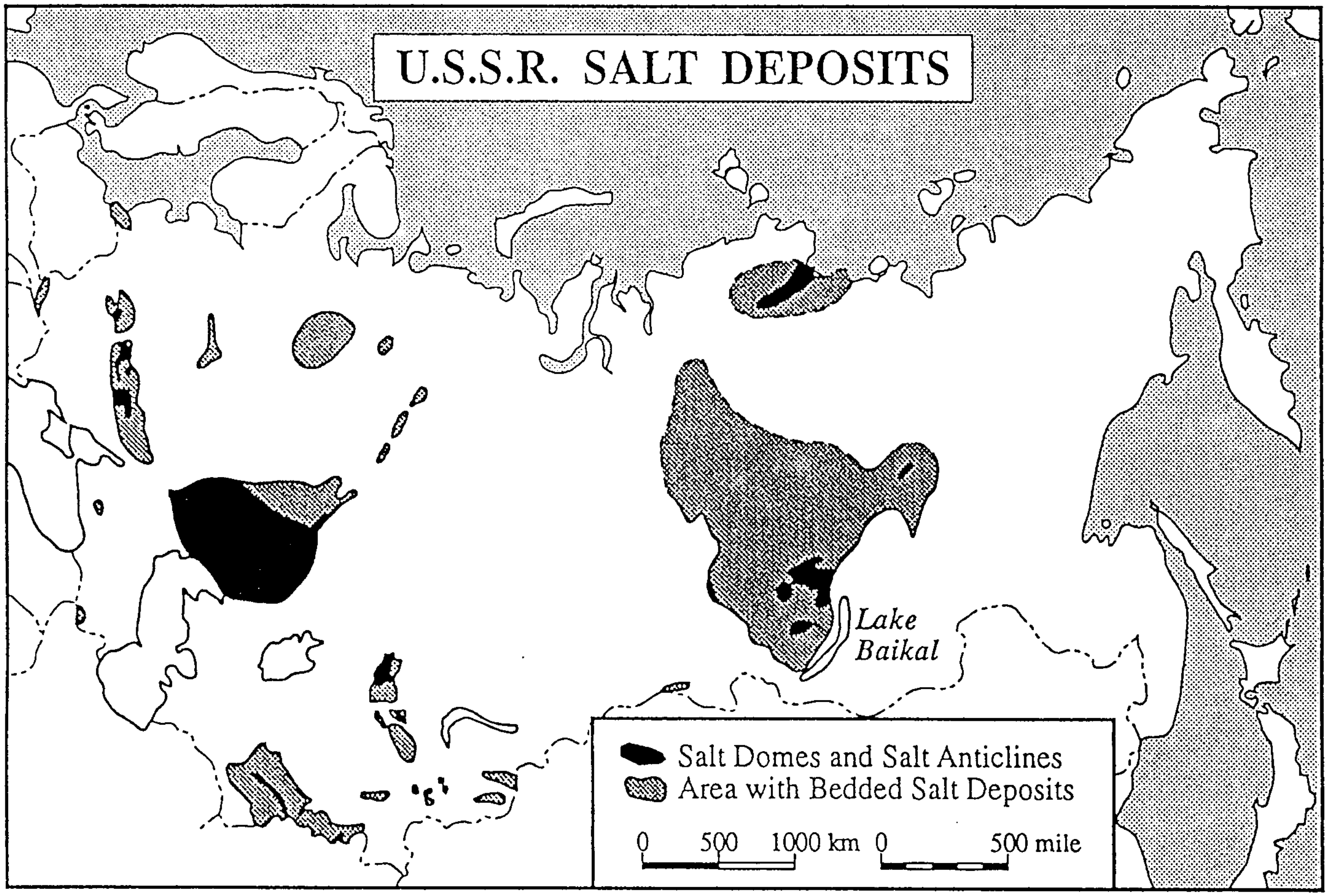

Figure.2. Areas of thick salt deposits of Former Soviet Union. Note area of massive salt domes to north of Caspian Sea in Pre-Caspian depression (large black area). Compiled from maps of Elias et al. [44] and Rachlin [45].

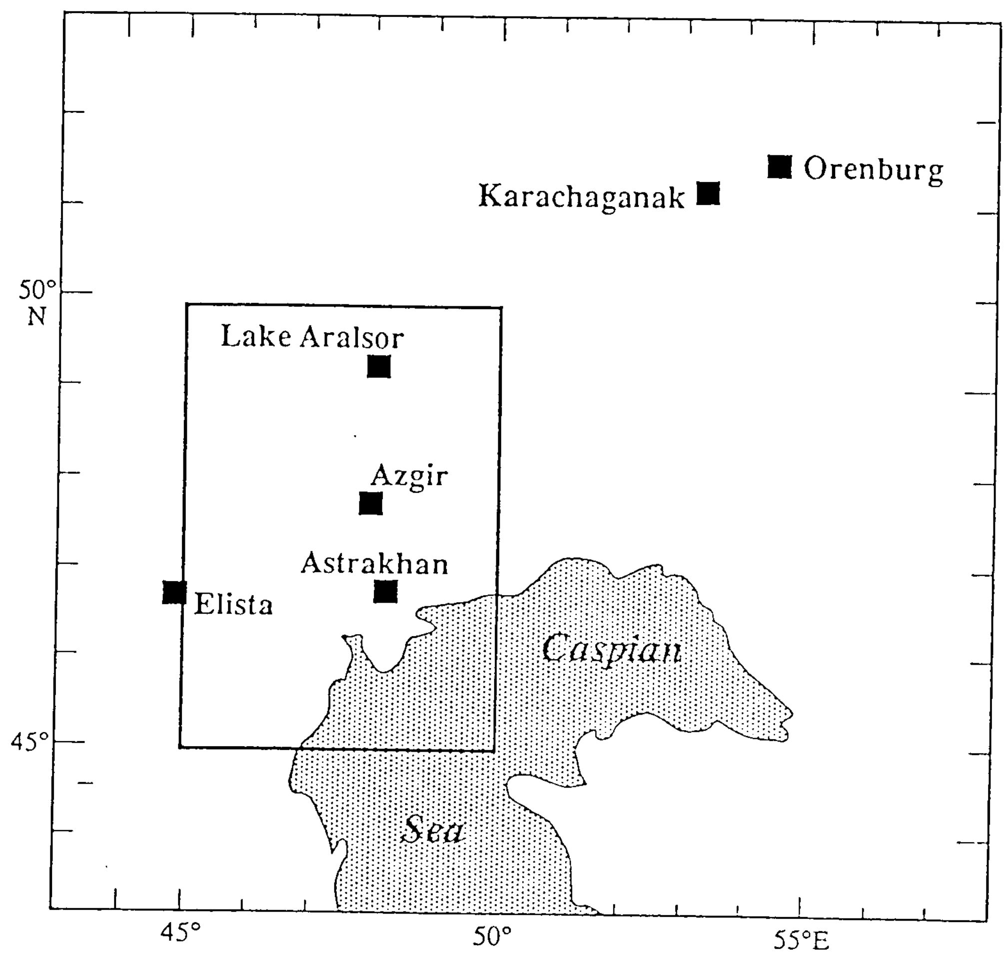

Figure 3. North Caspian Region showing sites of nuclear explosions in and near thick salt deposts (squares) in Pre-Caspian depression and area of special study of small seismic events (boxed region) shown in Figure 8.

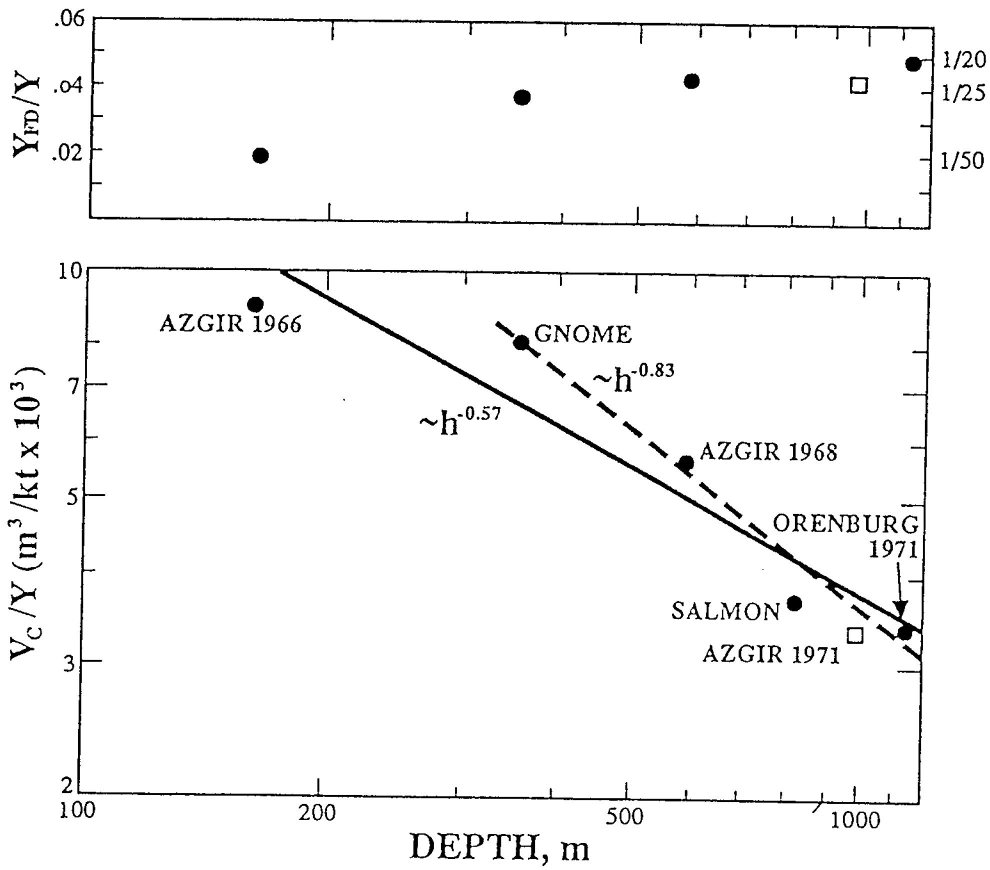

Figure 4. Top: Calculated maximum fully-decoupled yield, Y_{FD}, divided by yield, Y, of tamped explosion creating a cavity of usable volume V_C as a function of depth, h, for tamped nuclear explosions in salt for which information has been released on Y, h and V_C. Data from 1971 explosion were not included in either two regression lines shown. Solid line is regression based on data from four other explosions; dashed, that based on those four data points minus that for shallow event of 1966.

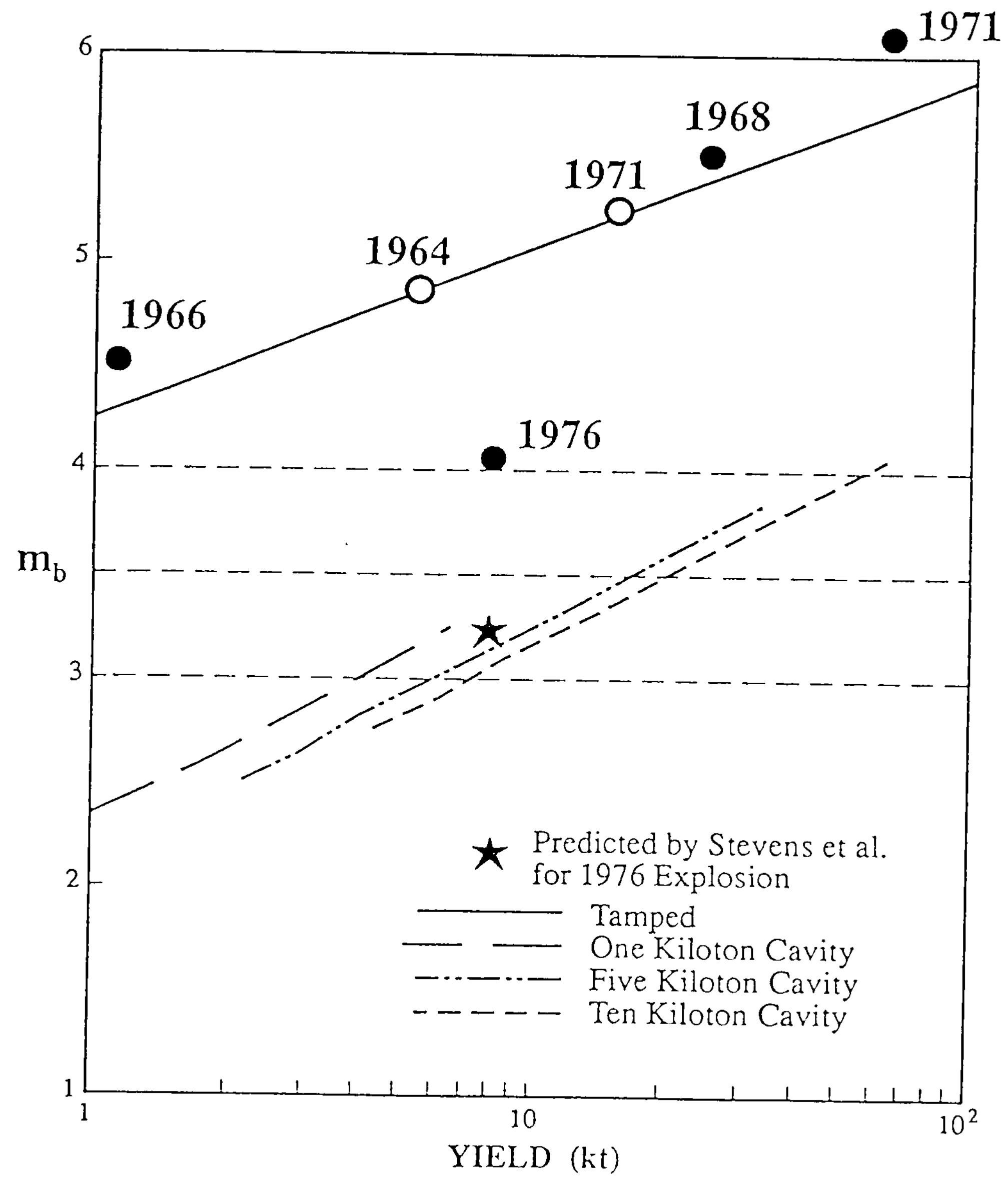

Figure 5. Magnitude, m_b, as a function of announced yield for five tamped and one partially decoupled nuclear explosions in salt. Solid symbols denote Azgir explosions. Four computed linear relatiionships are from Stevens et al. [16]. Eqn. (2), which was fit to the data points for the three tamped explosions at Azgir plus that for the 1971 Orenburg event, lies slightly above the solid line for tamped explosions of Stevens et al. that is shown here.

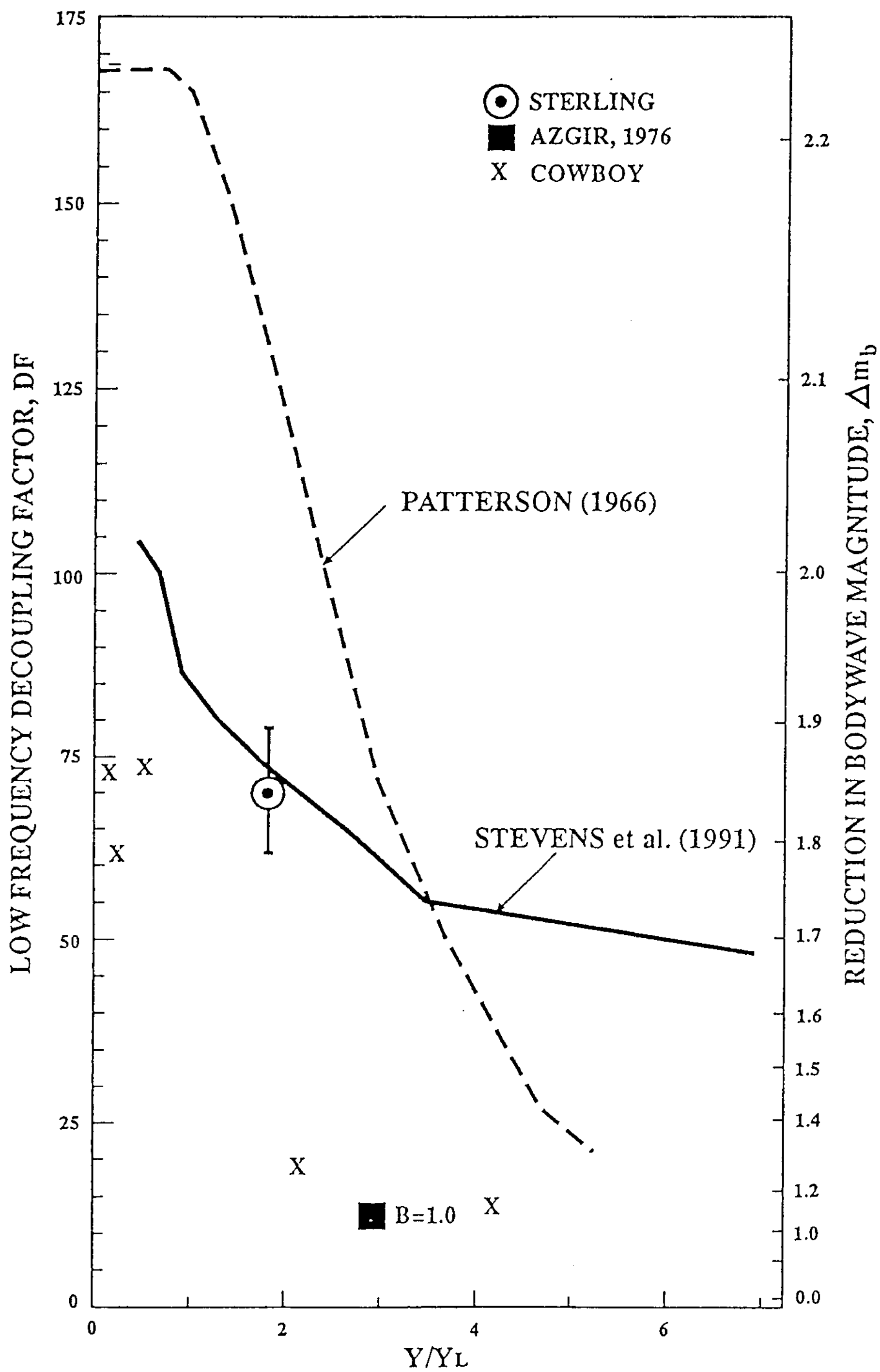

Figure 6. Low-frequency decoupling factor, DF, as a function of ratio of yield, Y, of partially decoupled explosion to yield of a fully decoupled explosion, Y_L. Note that data points fall below both theoretical calculations.

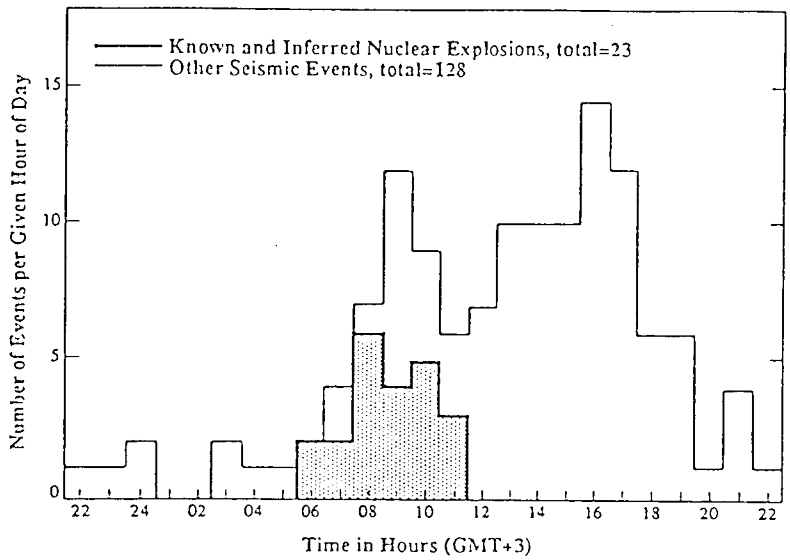

Figure 7. Histograms of times to nearest hour of day of known and inferred nuclear explosions (hatched region) and other seismic events in special study area near Azgir as outlined in Figure 3.

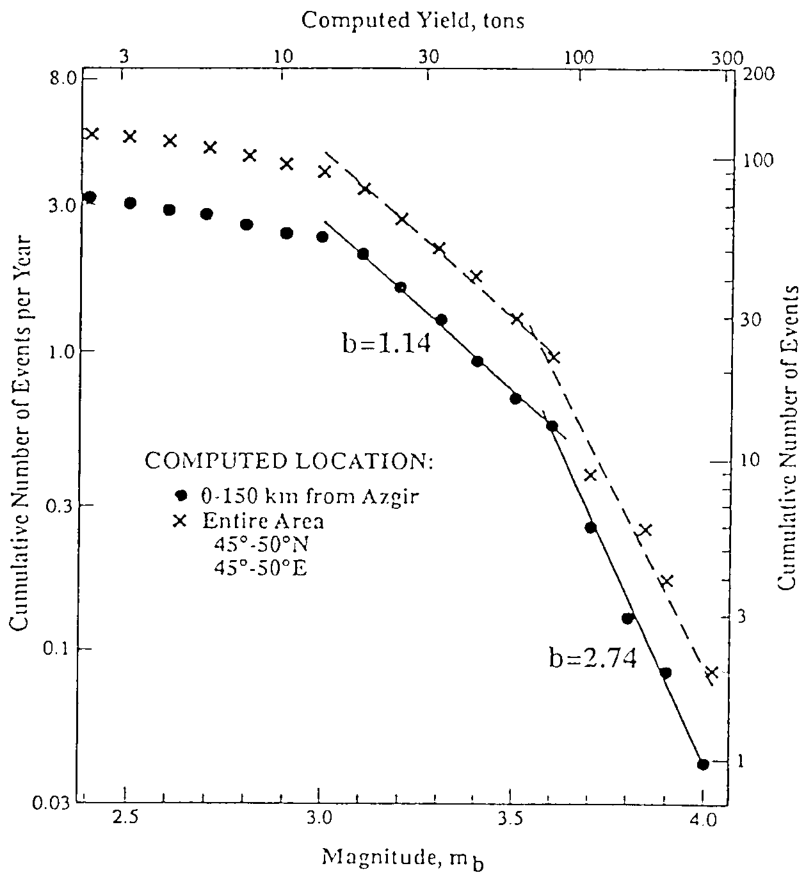

Figure 8. Cumulative number (N) of seismic events of magnitude $\geq m_b$ that are neither known nor inferred to be nuclear explosions in special study area outlined in Figure 3 (x's) and those located within 150 km of Azgir (solid circles). Most and perhaps all, events are chemical explosions as judged from histogram of origin times of events in Figure 7. Values of slope, **b**, fit by eye for relationship $\log N = a - \mathbf{b}m_b$.

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